EM: Inductive Sources

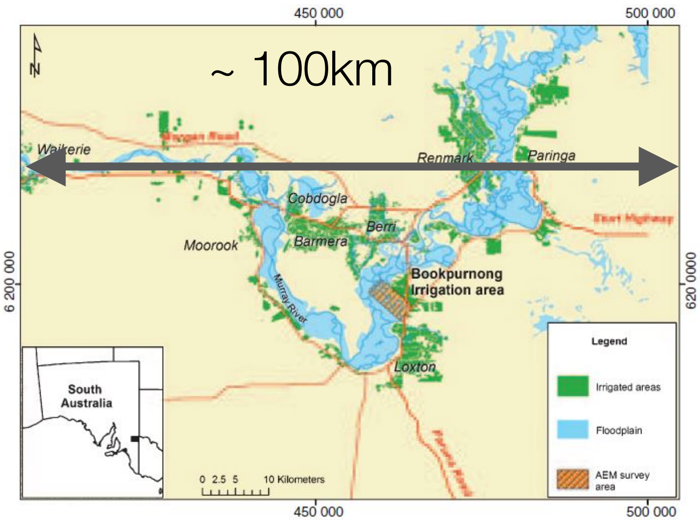
DISC

2017

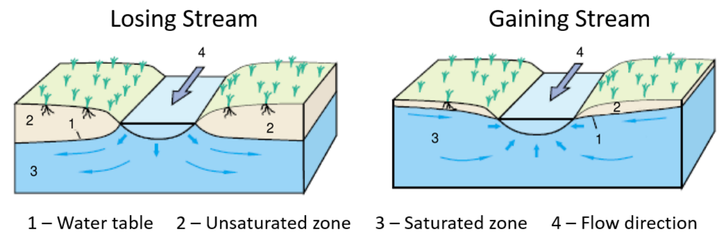
Electromagnetics
Fundamentals and Applications

Motivation

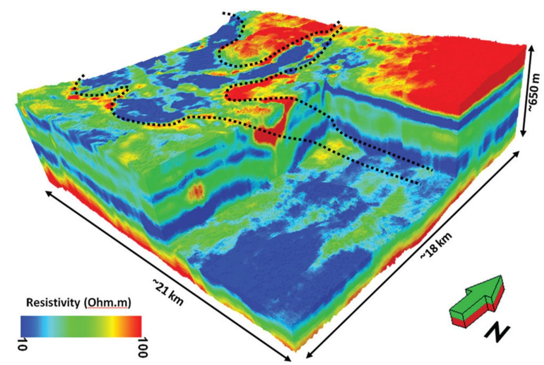
Large areas to be covered



Groundwater



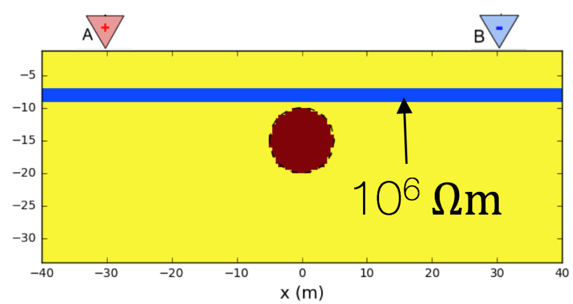
High resolution near surface



Rugged terrain

Minerals

Shielding problem



Outline

Setup

- Basic experiment
- Transmitters, Receivers

Time Domain EM

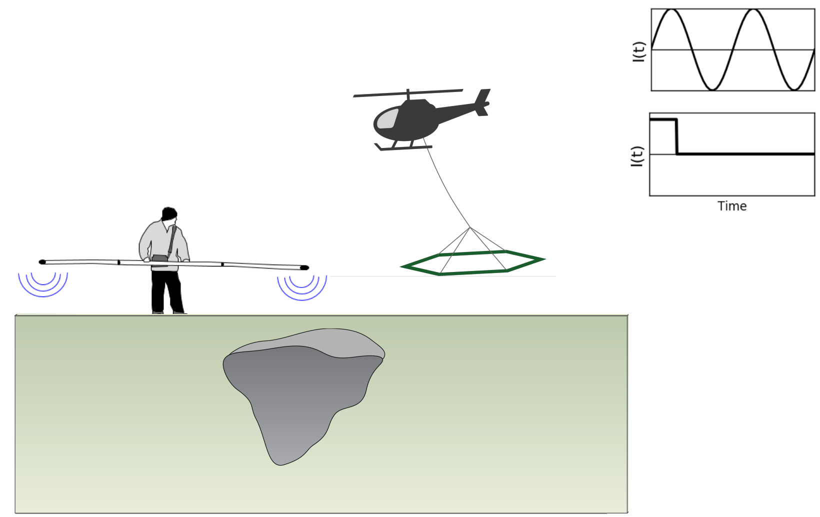
- Vertical Magnetic Dipole
- Propagation with Time
- Case History – Groundwater, Hydrocarbons

Frequency Domain EM

- Vertical Magnetic Dipole
- Effects of Frequency
- Case History – Groundwater

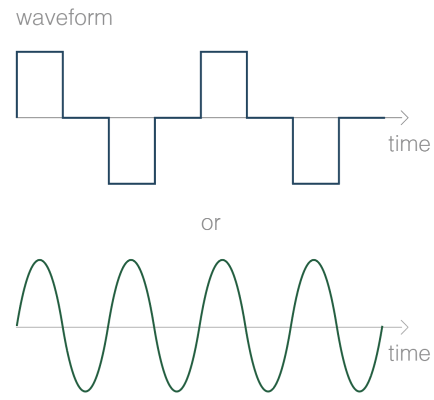
Important questions

- What is the target?
  - at the surface? At depth?. 1D, 2D, 3D?
- Transmitter
  - Location: surface? in the air?
  - Waveform: frequency or time?
  - “Size” and orientation?
- Exciting the target
  - Conductivity of the target and host
  - Geometry of the target (Coupling)
- Receiver and data
  - What fields to measure?
  - What instrument?



- Where to collect data? How many? How accurate?
- What is depth of investigation?
- What is the “footprint” of the transmitter”
  - These are questions of **SURVEY DESIGN**

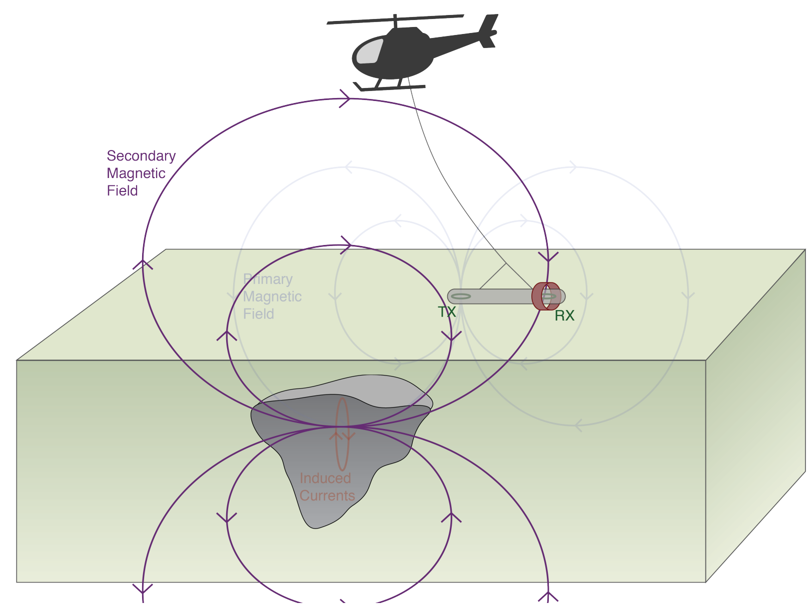
Basic Experiment



- **Transmitter:**
  - Produces a primary magnetic field

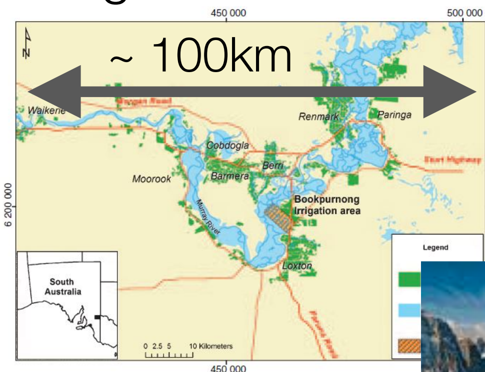
- **Exciting the target:**
  - Time varying magnetic fields generate electric fields everywhere
  - Producing currents in conductors

- **Receiver:**
  - Induced currents produce secondary magnetic fields



Transmitter

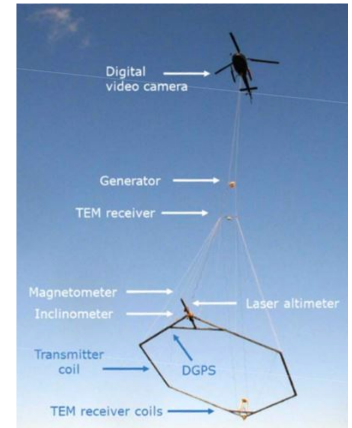
Large areas



Rugged terrain

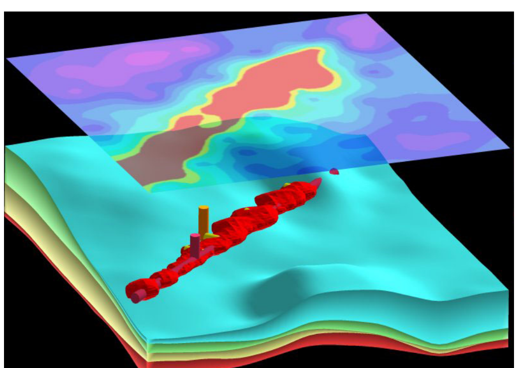
Airborne Survey

Resolve

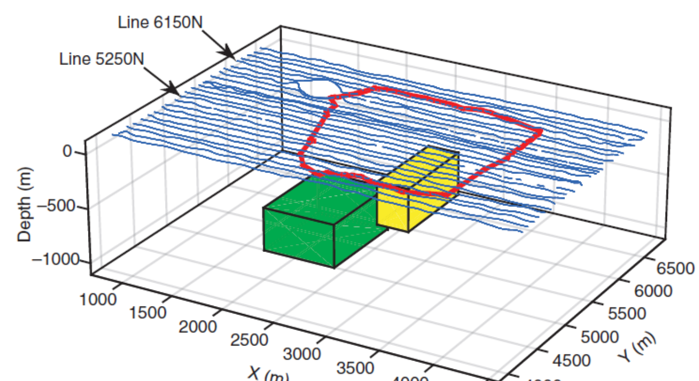


SkyTEM

Deep Targets

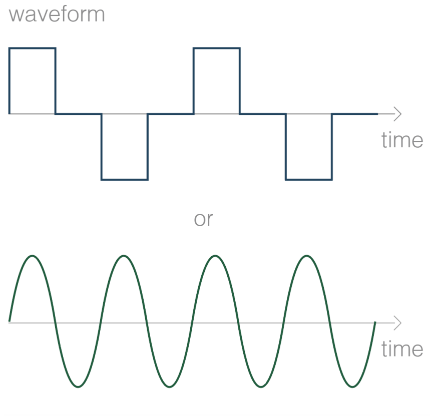


Large Loop



Transmitter

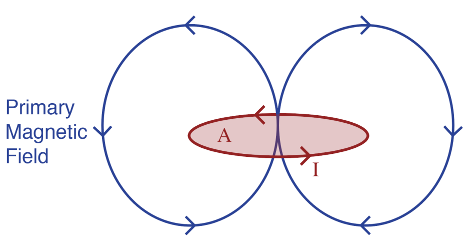
- Time or frequency?



- Key factor is moment

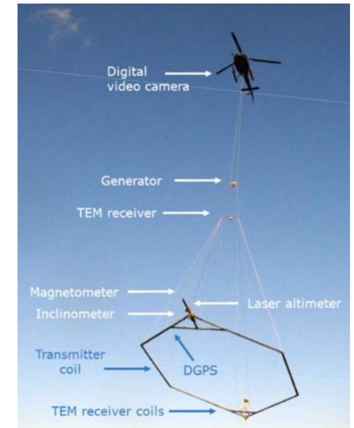
$$m = I \text{ (current) } A \text{ (area) } N \text{ (\# of turns)}$$

$$\mathbf{B}(\mathbf{r}) = \frac{\mu_0}{4\pi}\left(\frac{3\mathbf{r}(\mathbf{m}\cdot\mathbf{r})}{|\mathbf{r}|^5} - \frac{\mathbf{m}}{|\mathbf{r}|^3}\right)$$



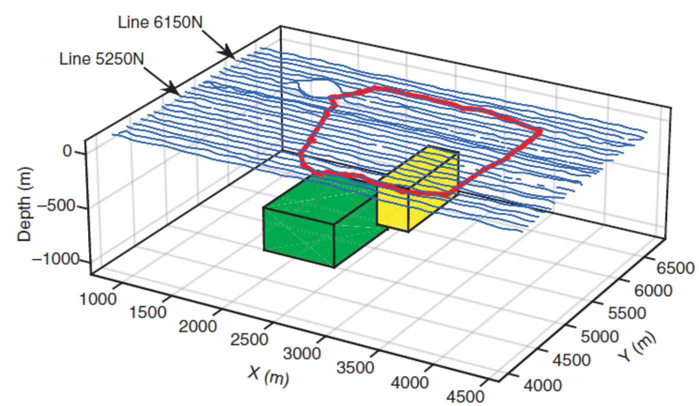
Airborne Survey

Resolve



SkyTEM

Large Loop

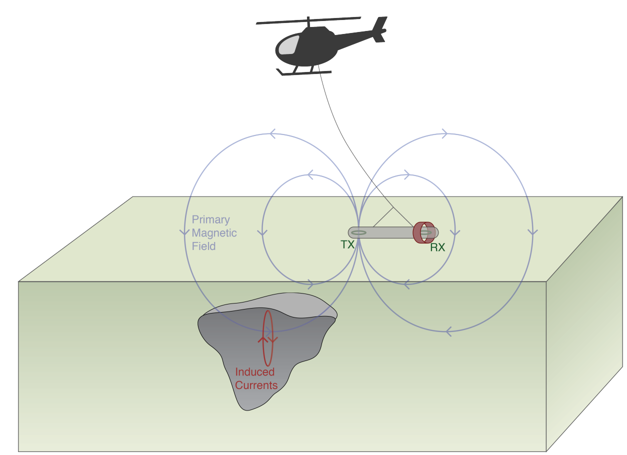


Exciting the target

- Primary field from a loop

$$\mathbf{B}(\mathbf{r}) = \frac{\mu_0}{4\pi}\left(\frac{3\mathbf{r}(\mathbf{m}\cdot\mathbf{r})}{|\mathbf{r}|^5} - \frac{\mathbf{m}}{|\mathbf{r}|^3}\right)$$

- Fields fall off
  - $1/r^3$ geometric decay
  - Attenuation
- Want to be as close as possible to target
  - Ground based systems
  - Helicopter
  - Fixed wing aircraft
- Always concerned about coupling

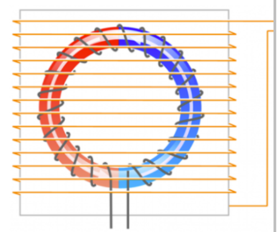


Receiver and Data

Magnetometer

$$\mathbf{b}(t)$$

- Measures:
  - Magnetic field
  - 3 components
- eg. 3-component fluxgate

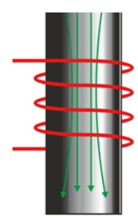


Fluxgate

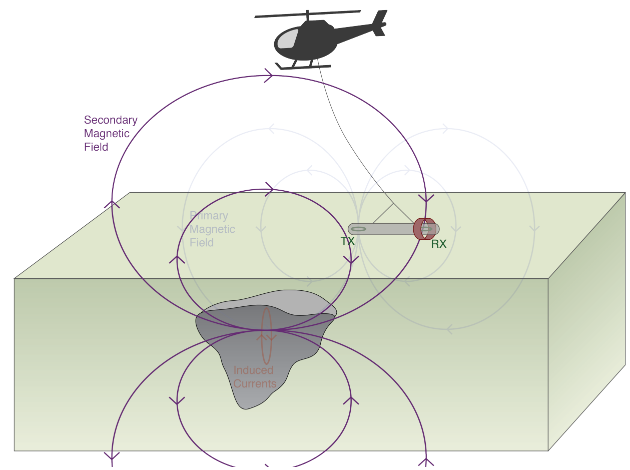
Coil

$$\frac{\partial b}{\partial t}$$

- Measures:
  - Voltage
  - Single component that depends on coil orientation
    - Coupling matters
- eg. airborne frequency domain.
  - ratio of Hs/Hp is the same as Vs/Vp



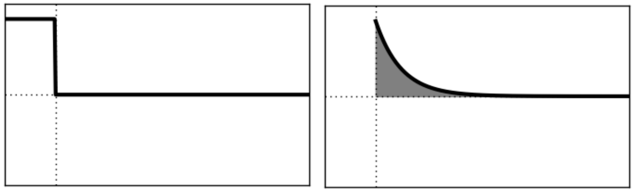
Coil



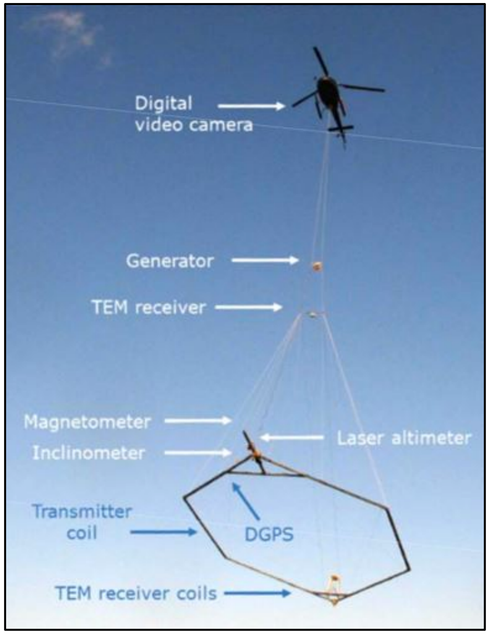
Receiver: Time Domain

- Primary field has off-time
- Measure secondary fields
- Receivers can be mounted on transmitter loop or above it

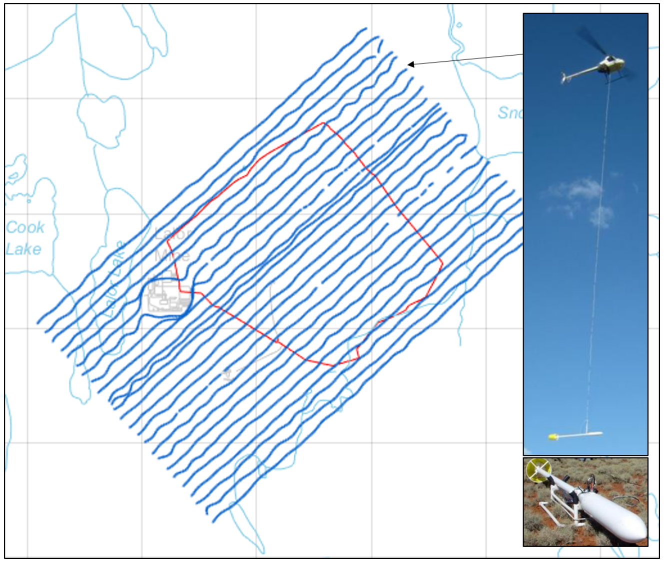
Current Response



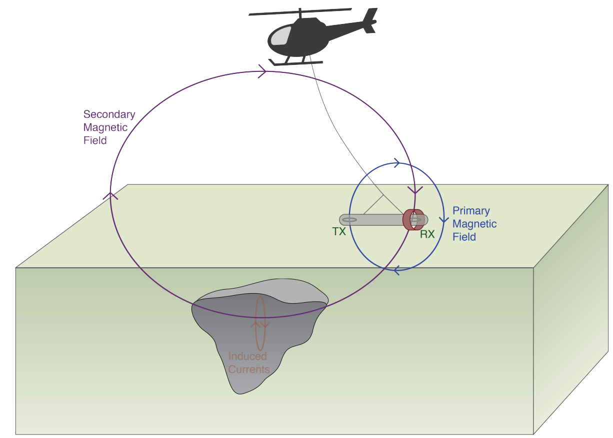
SkyTEM



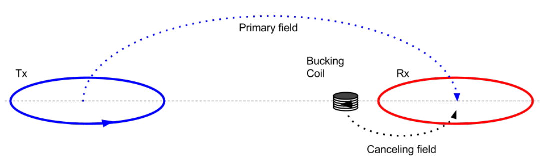
HeliSAM



Receiver: Frequency Domain

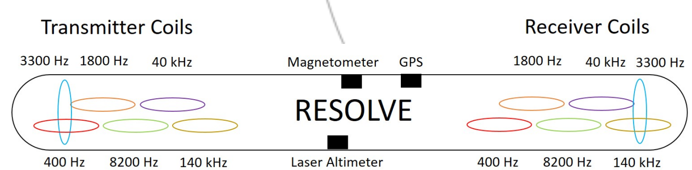


- Primary field
  - always “on”
  - large compared to secondary fields
- Primary removal
  - Compute and subtract
  - Bucking coil

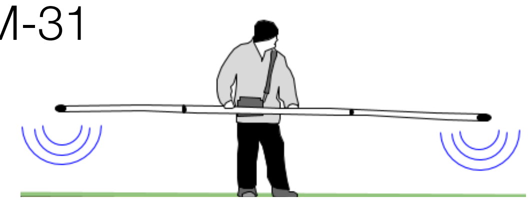


- Main requirement:
  - Know positions of Tx and Rx
  - Keep them in one unit

Resolve



EM-31



Important questions

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- Transmitter
  - Location: surface? in the air?
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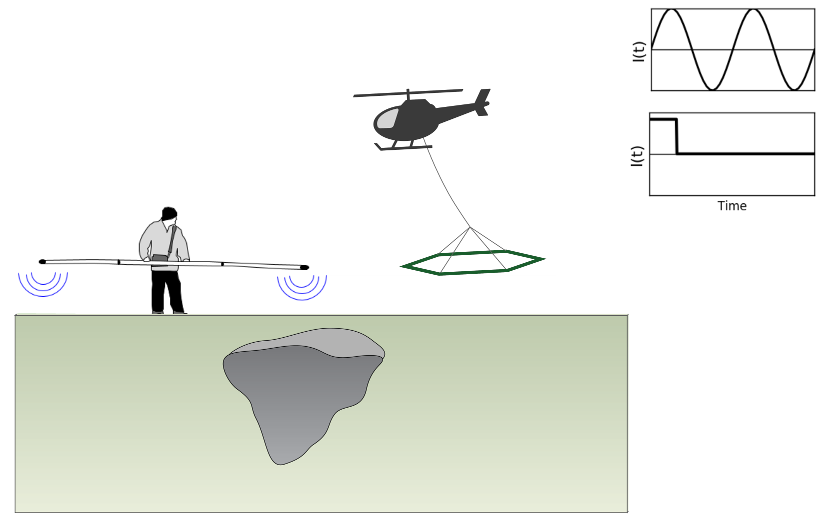

- Where to collect data? How many? How accurate?
- What is depth of investigation?
- What is the “footprint” of the transmitter”
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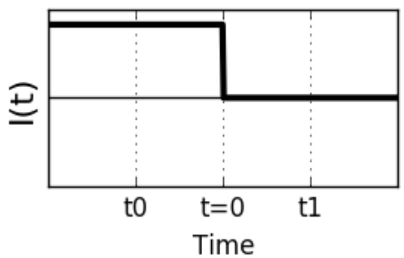
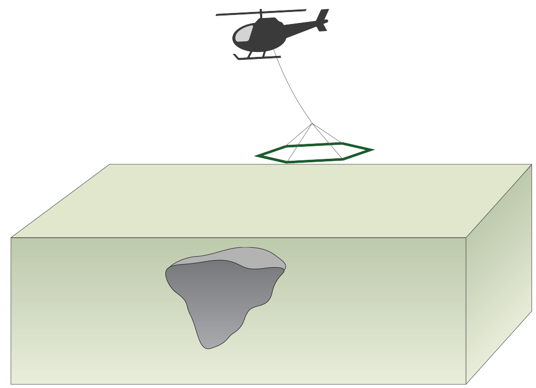
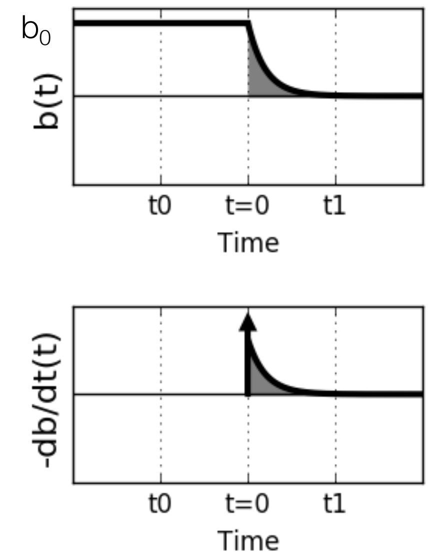
EM with Inductive Sources: Time Domain

Transmitter current





Receiver



time	**b**	**db/dt**
$t < 0$	b_0	0
$t = 0$	b_0	$-b_0\delta(t)$
$t > 0$	secondary	secondary

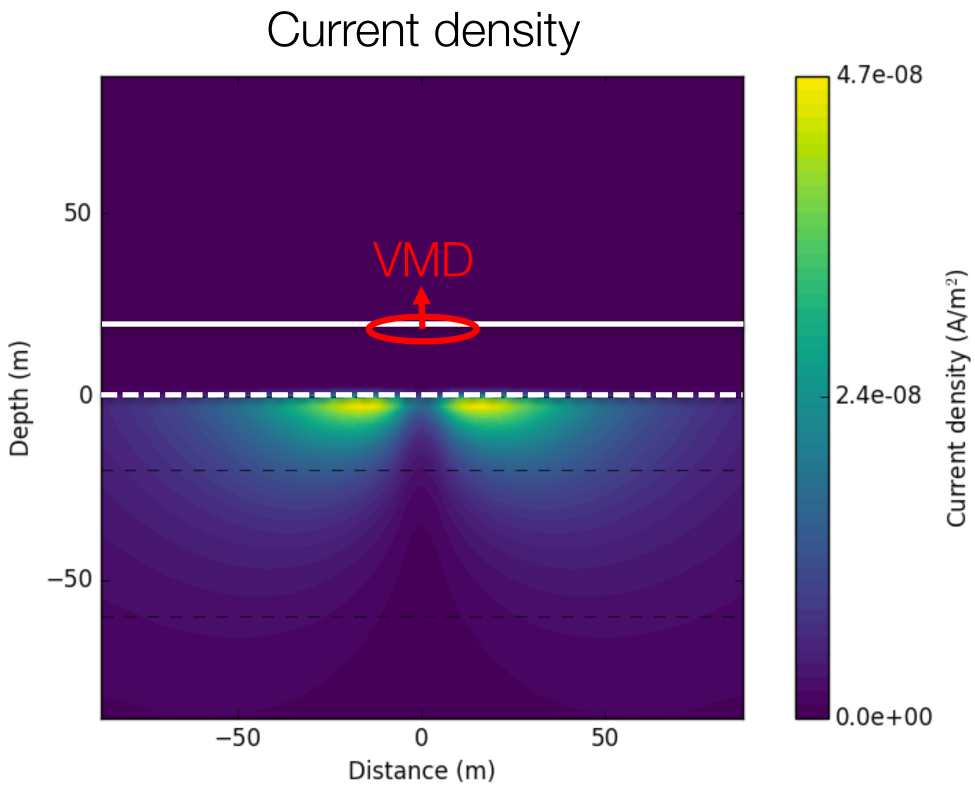
$\delta(t)$: Dirac-delta function

Footprint of Airborne EM system

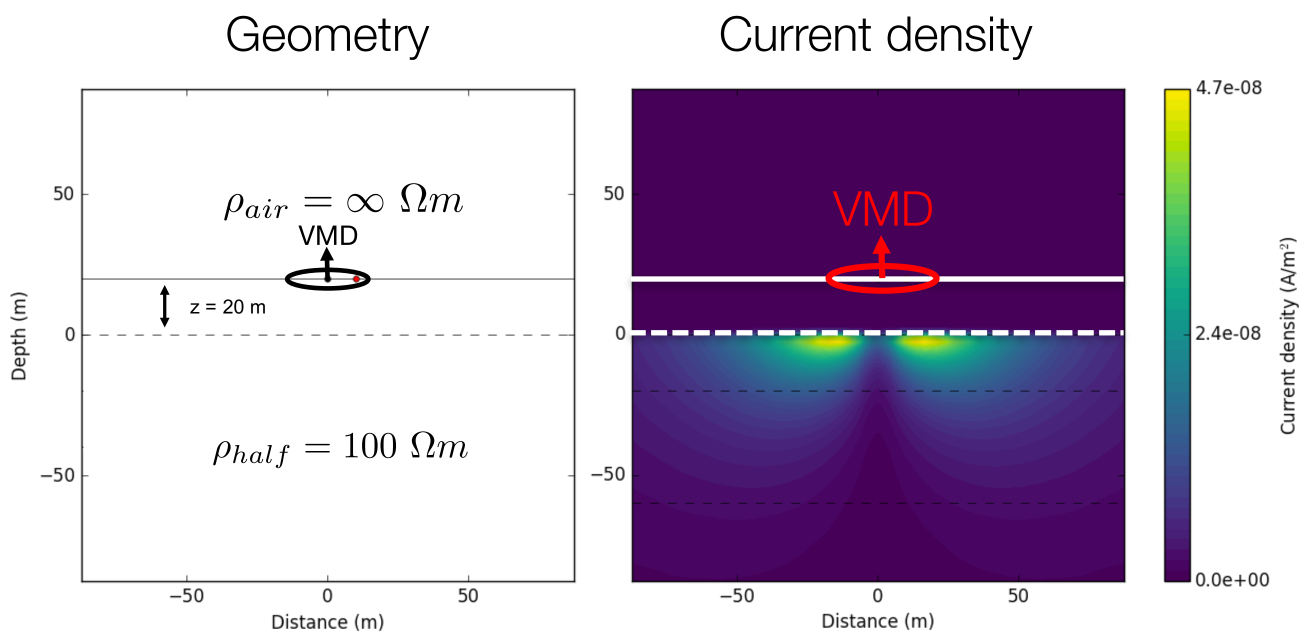
- What volume of earth is “seen” by the airborne system?
  - Where are the currents?

- Currents depend on
  - Transmitter
  - Waveform: time or frequency
  - Background conductivity

- Simple case: loop source over homogeneous earth

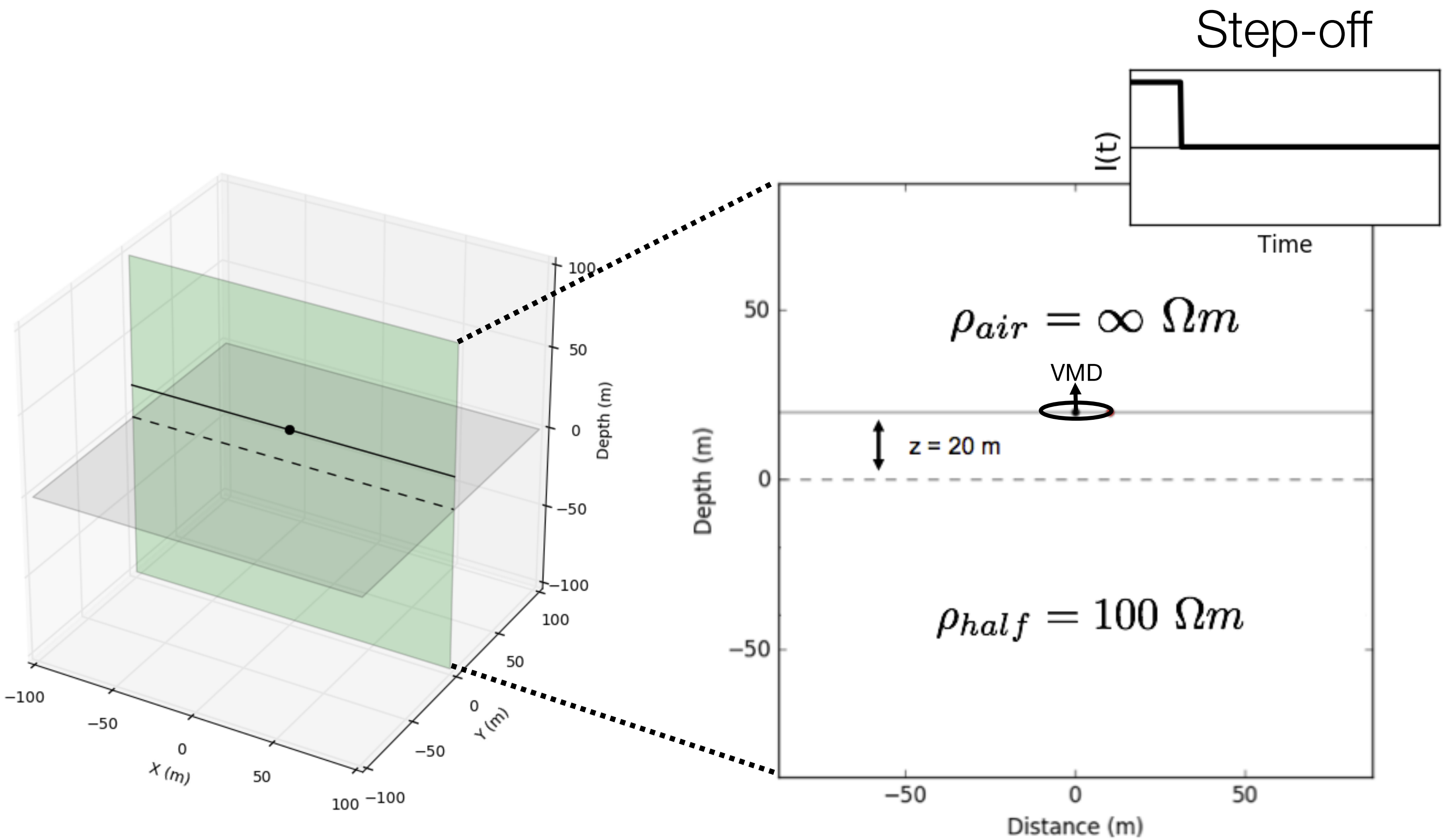


Vertical Magnetic Dipole (VMD)



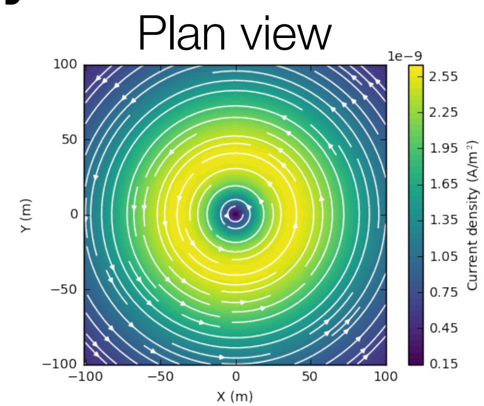
- Some questions
  - Where, and how strong, are the currents?
  - How do they depend upon the conductivity?
  - What do the resulting magnetic fields look like?

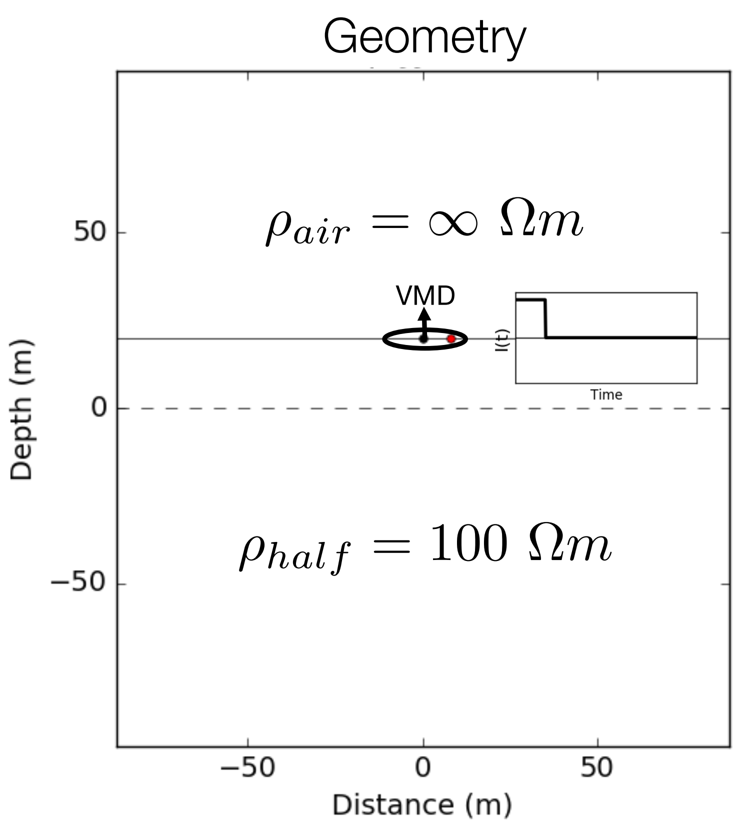
Vertical Magnetic Dipole over a halfspace (TDEM)

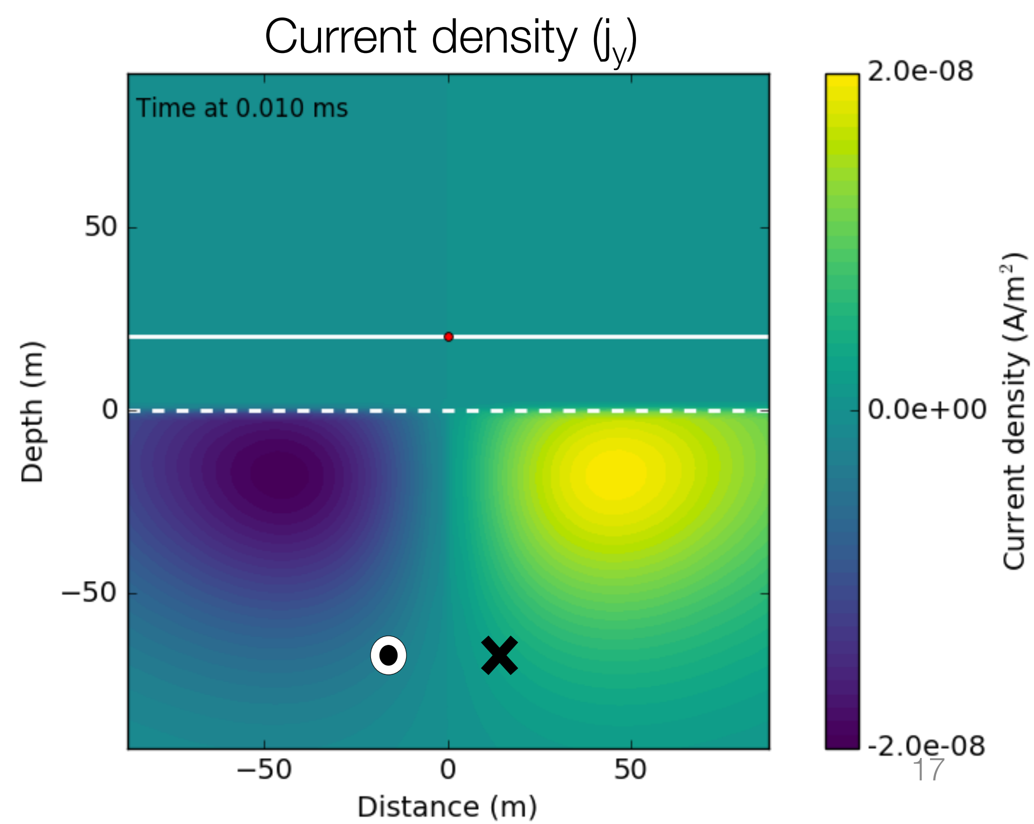


Current Density

- Time: 0.01ms

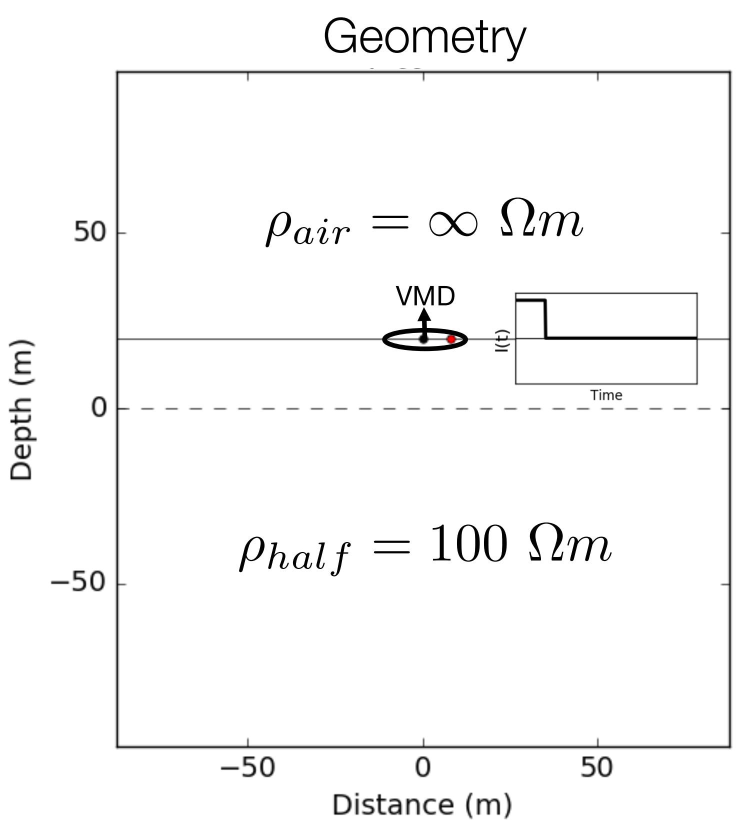


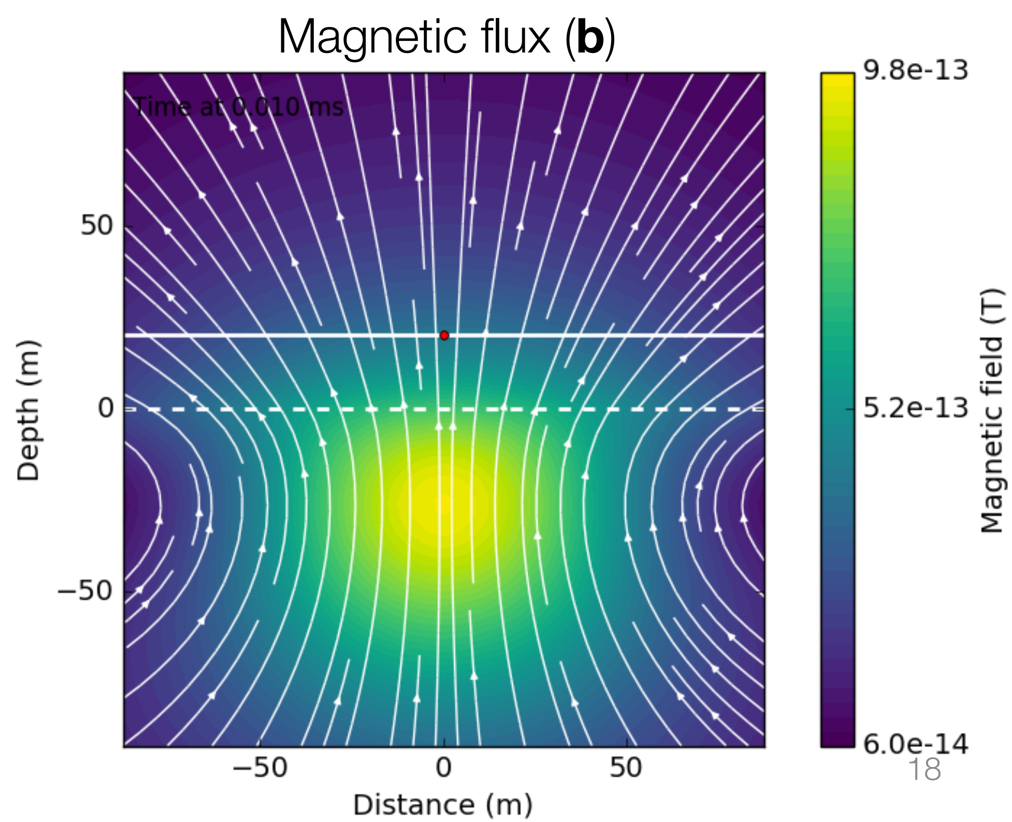




Magnetic flux density

- Time: 0.01ms

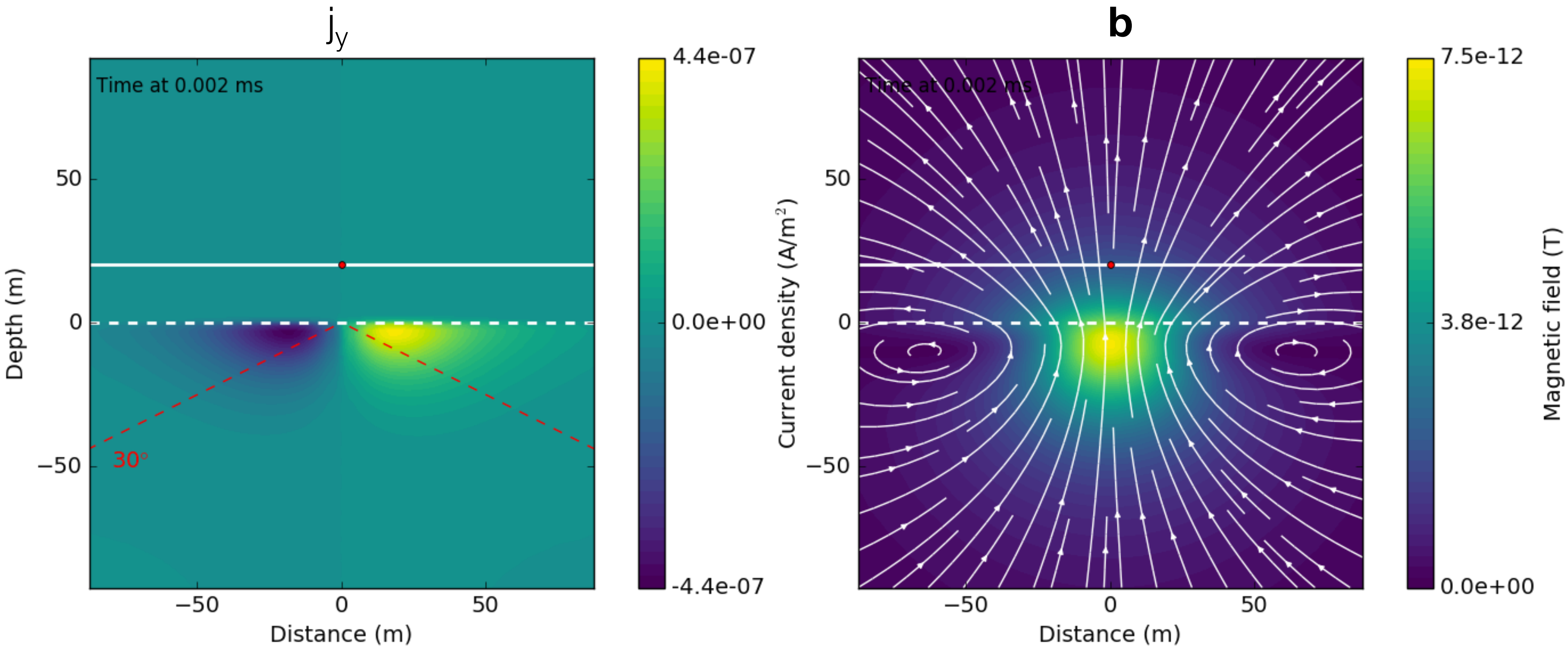




Propagation through time

- Time: 0.002ms
- diffusion distance = 18 m

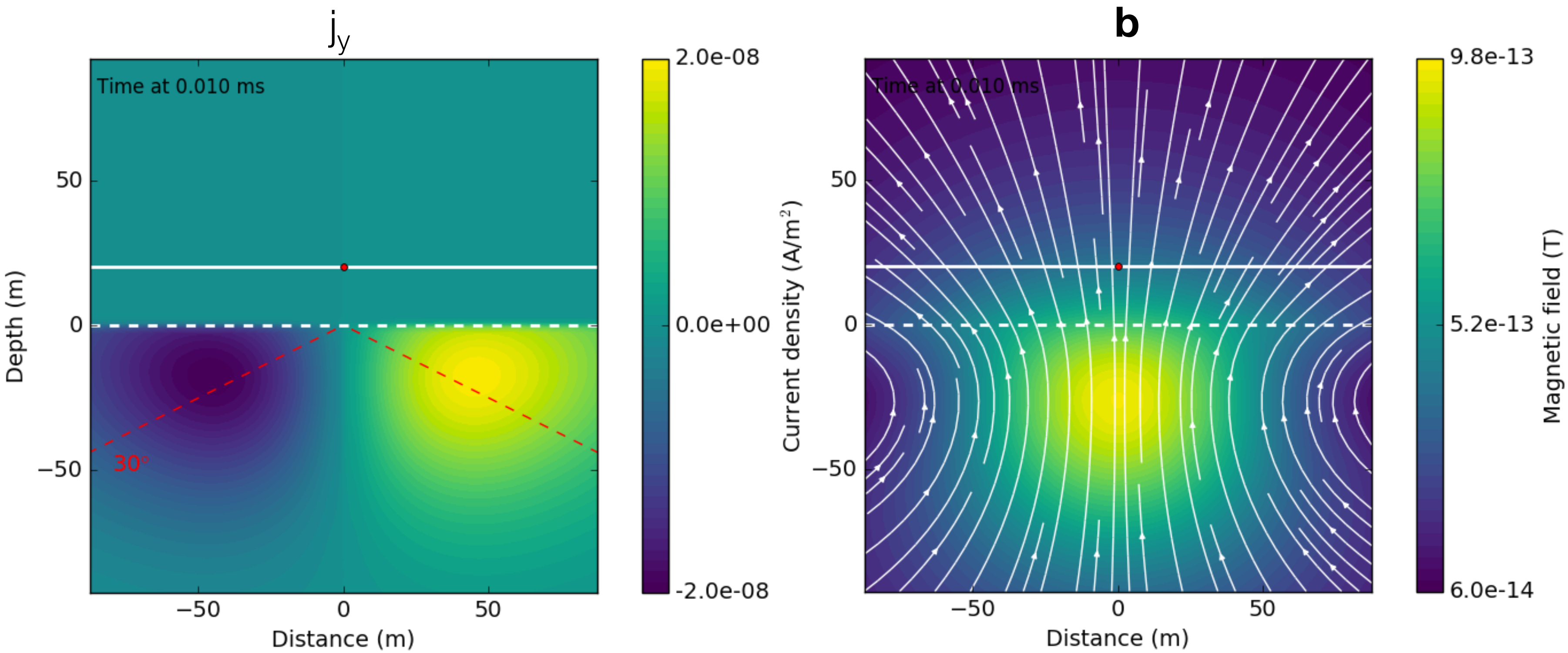
$$d = 1260\sqrt{t\rho}$$



Propagation through time

- Time: 0.01ms
- diffusion distance = 38 m

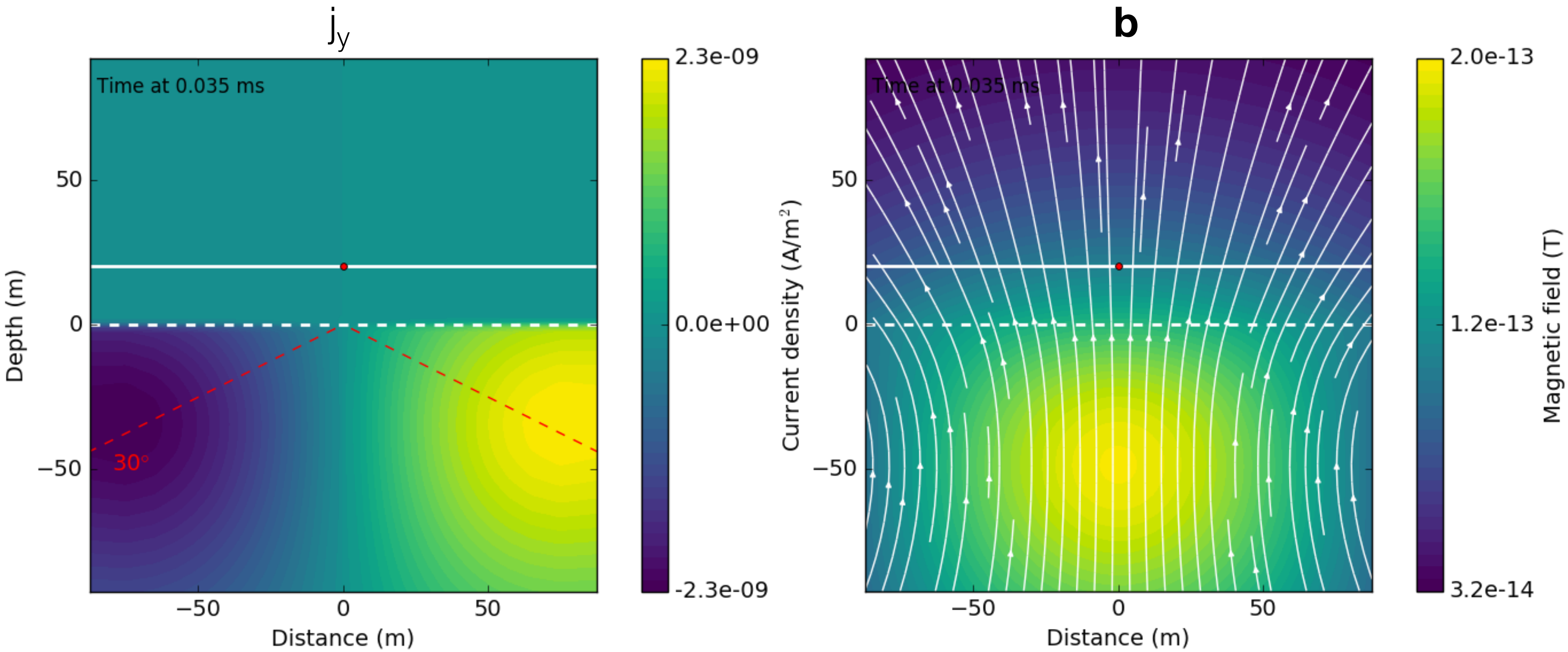
$$d = 1260\sqrt{t\rho}$$



Propagation through time

- Time: 0.035ms
- diffusion distance = 75 m

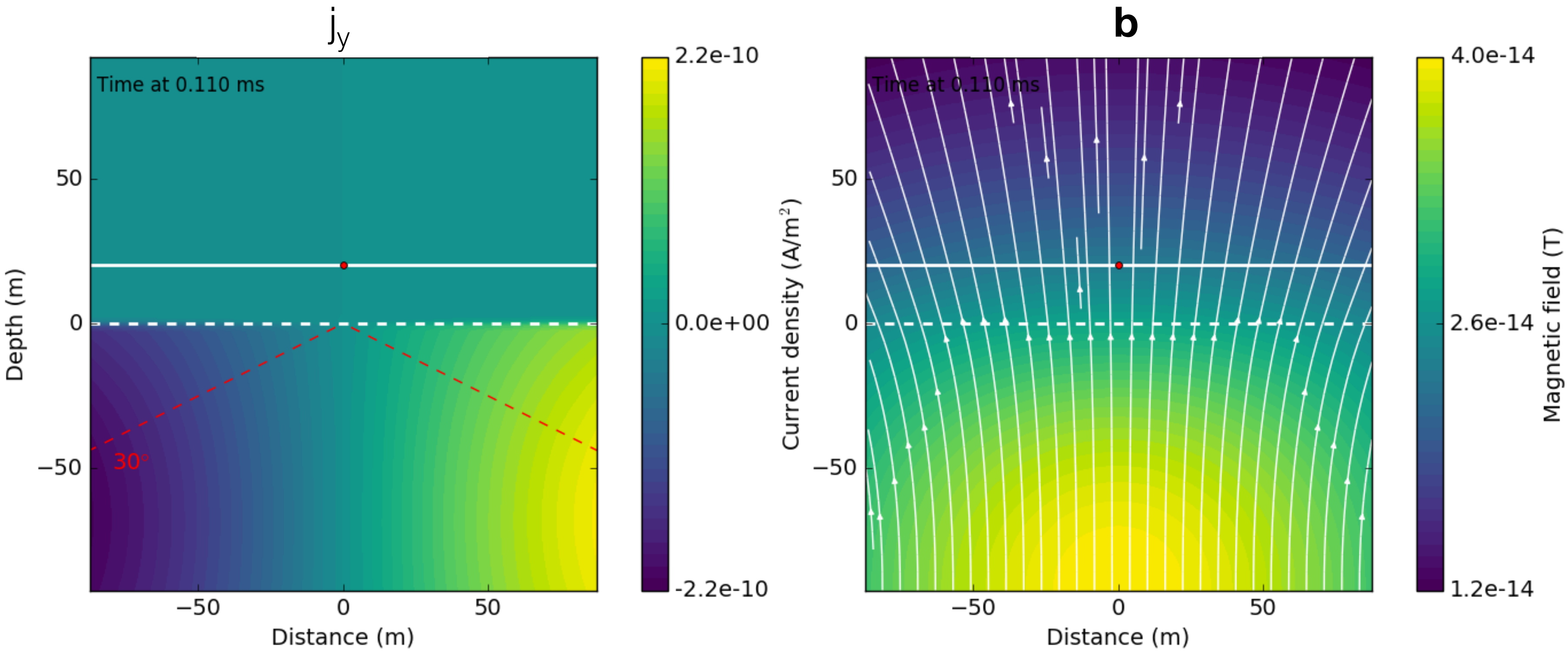
$$d = 1260\sqrt{t\rho}$$



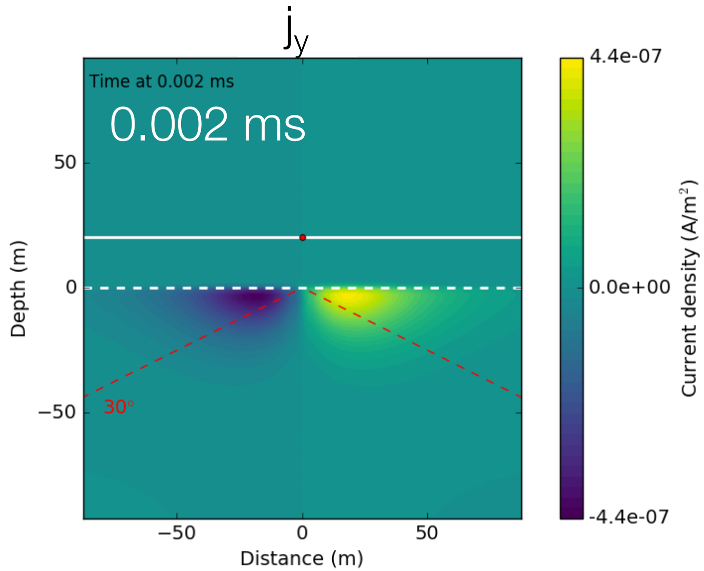
Propagation through time

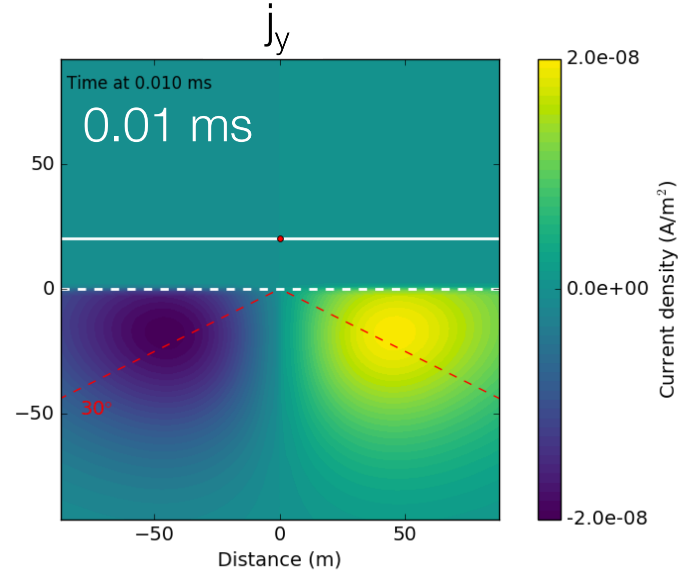
- Time: 0.110ms
- diffusion distance = 132 m

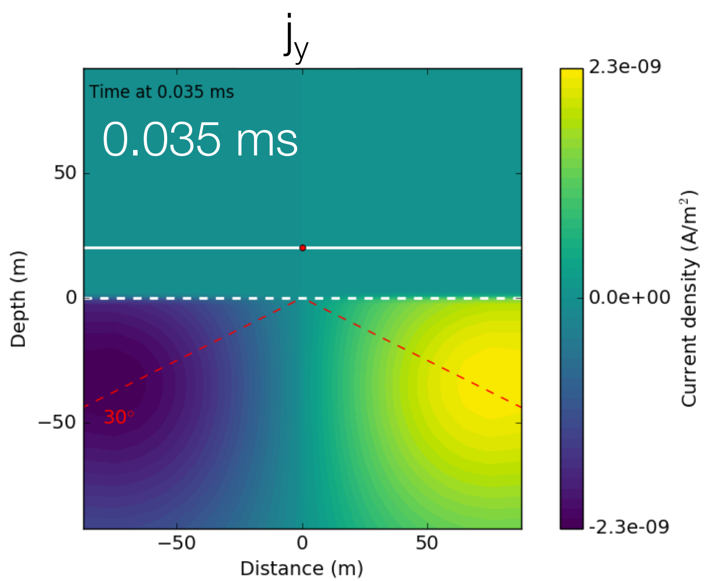
$$d = 1260\sqrt{t\rho}$$



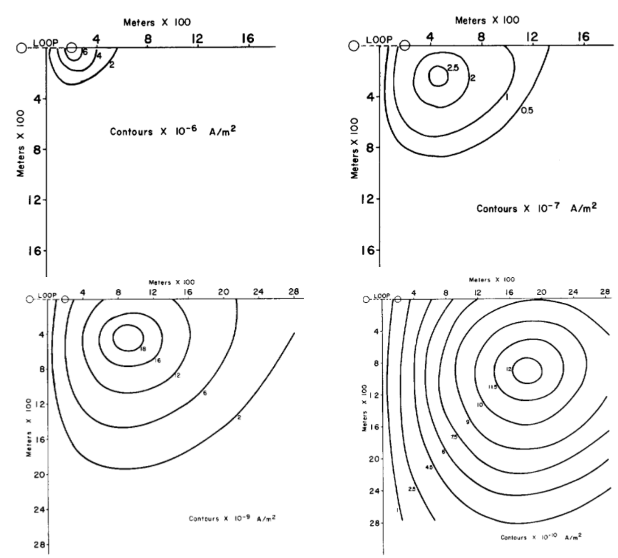
Summary: propagation through time







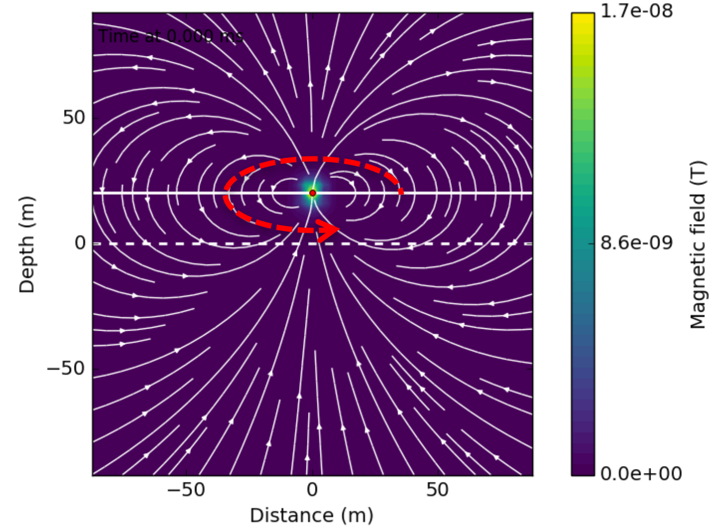
Nabighian (1979)



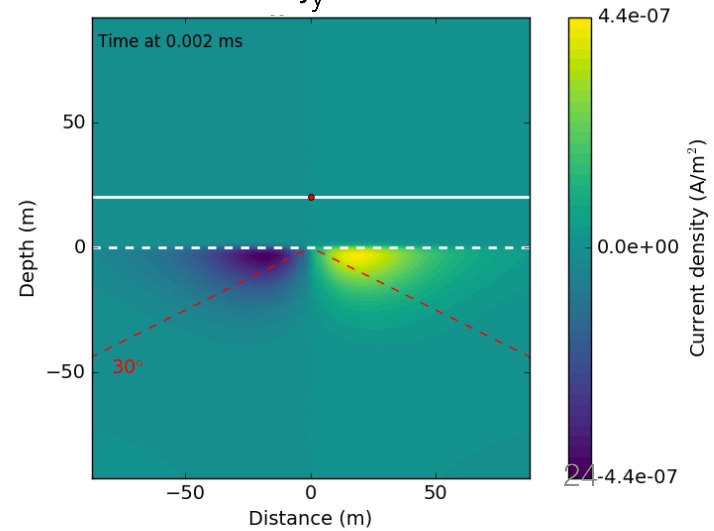
Important points

- Currents flow in same plane as transmitter currents
- Currents diffuse outward downward
- Each transmitter has a "footprint"
- Max resolution controlled by earliest time
- Depth of investigation controlled by latest time

magnetic field (on-time)



j_y



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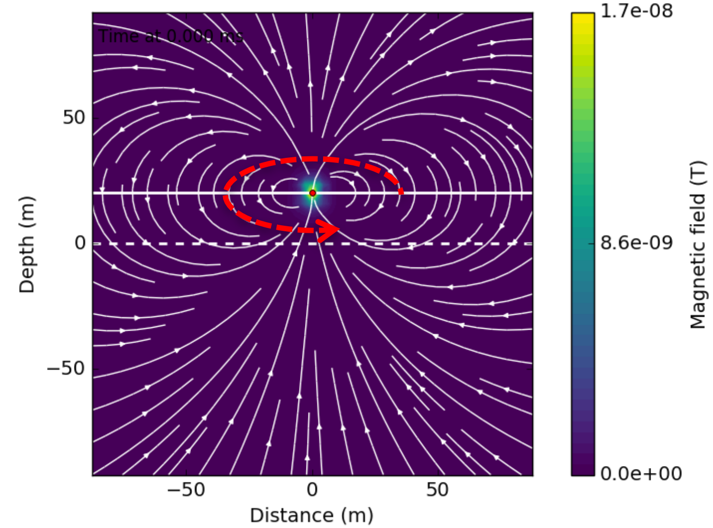
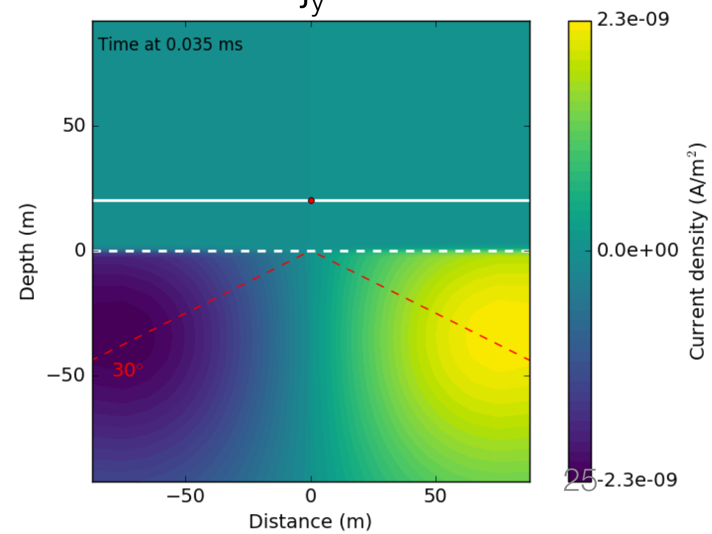
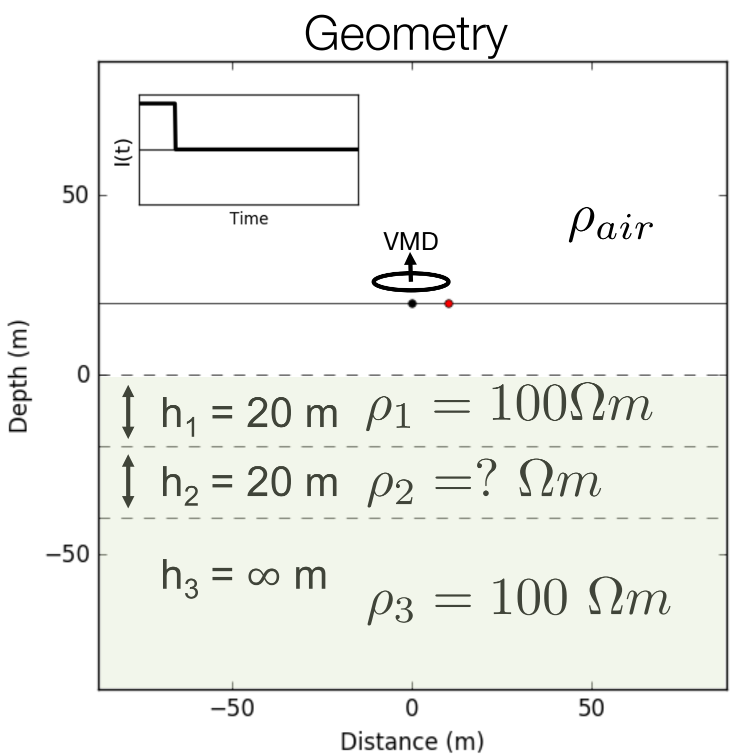


j_y



Layered earth

- 3 layers + air,
- ρ_2 varies



- Four different cases:
  - Halfspace

    ρ_2 = 100 Ωm
  - Resistive

    ρ_2 = 1000 Ωm
  - Conductive

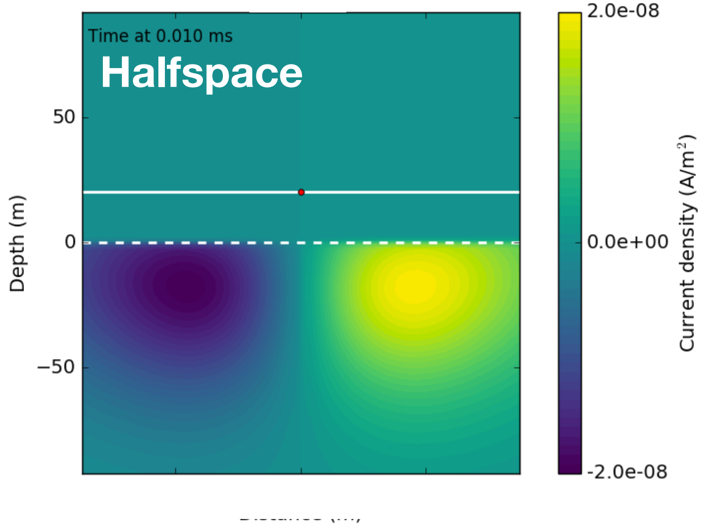
    ρ_2 = 10 Ωm
  - Very conductive

    ρ_2 = 1 Ωm

- Fields
  - j_y off-time
  - **b** off-time

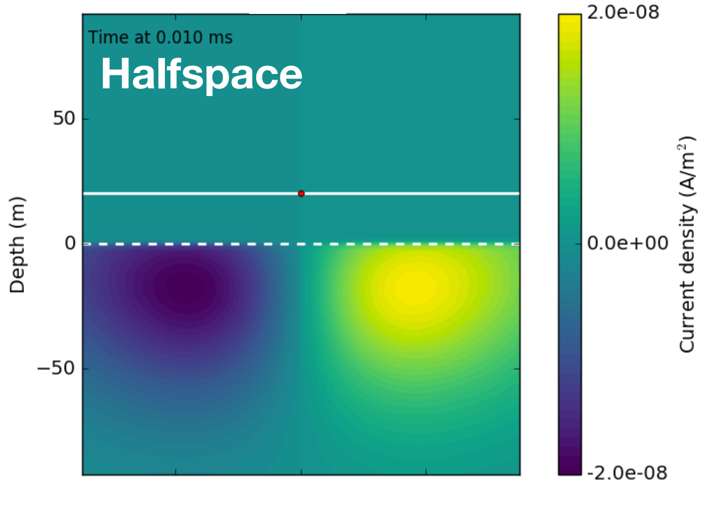
Layered earth currents (j_y)

$\rho_2 = 100\ \Omega m$

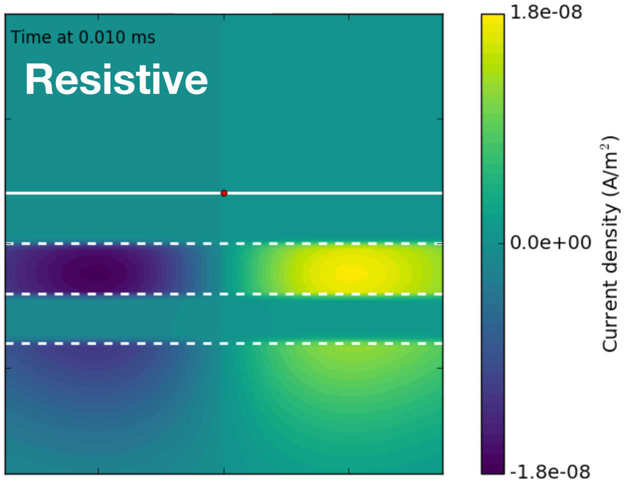


Layered earth currents (j_y)

$\rho_2 = 100\ \Omega m$

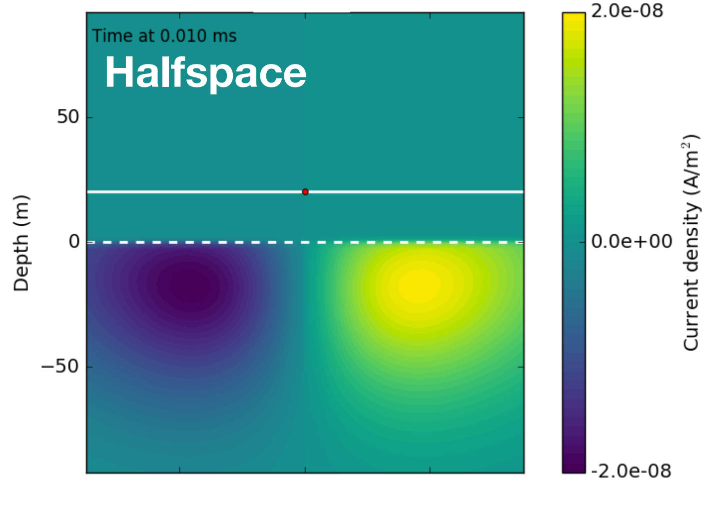


$\rho_2 = 1000\ \Omega m$

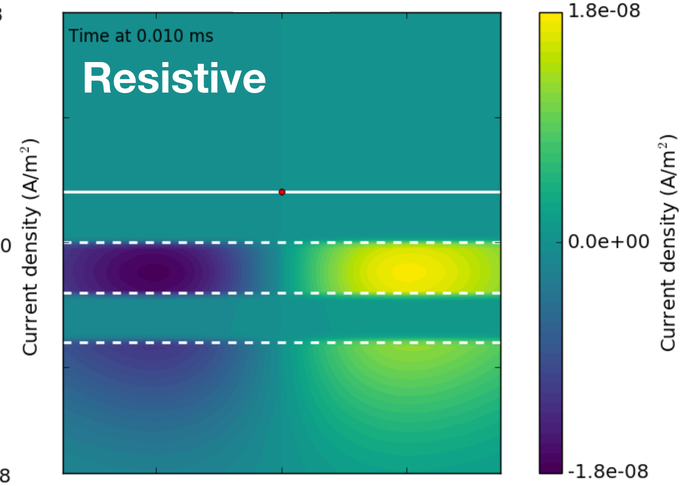


Layered earth currents (j_y)

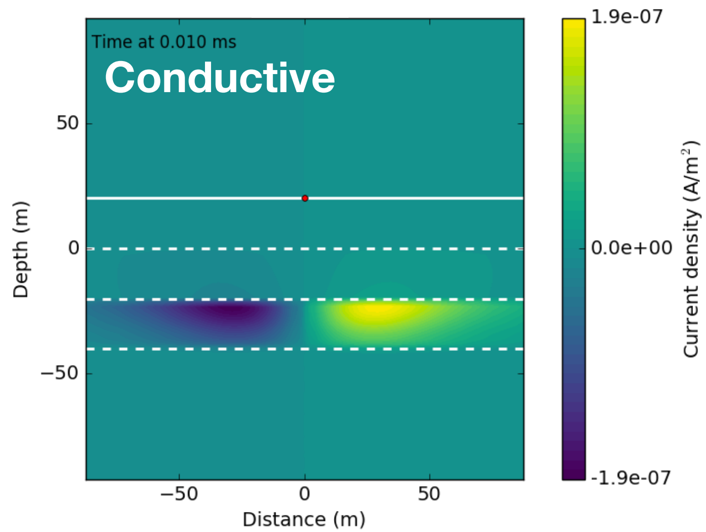
$\rho_2 = 100\ \Omega\mathrm{m}$



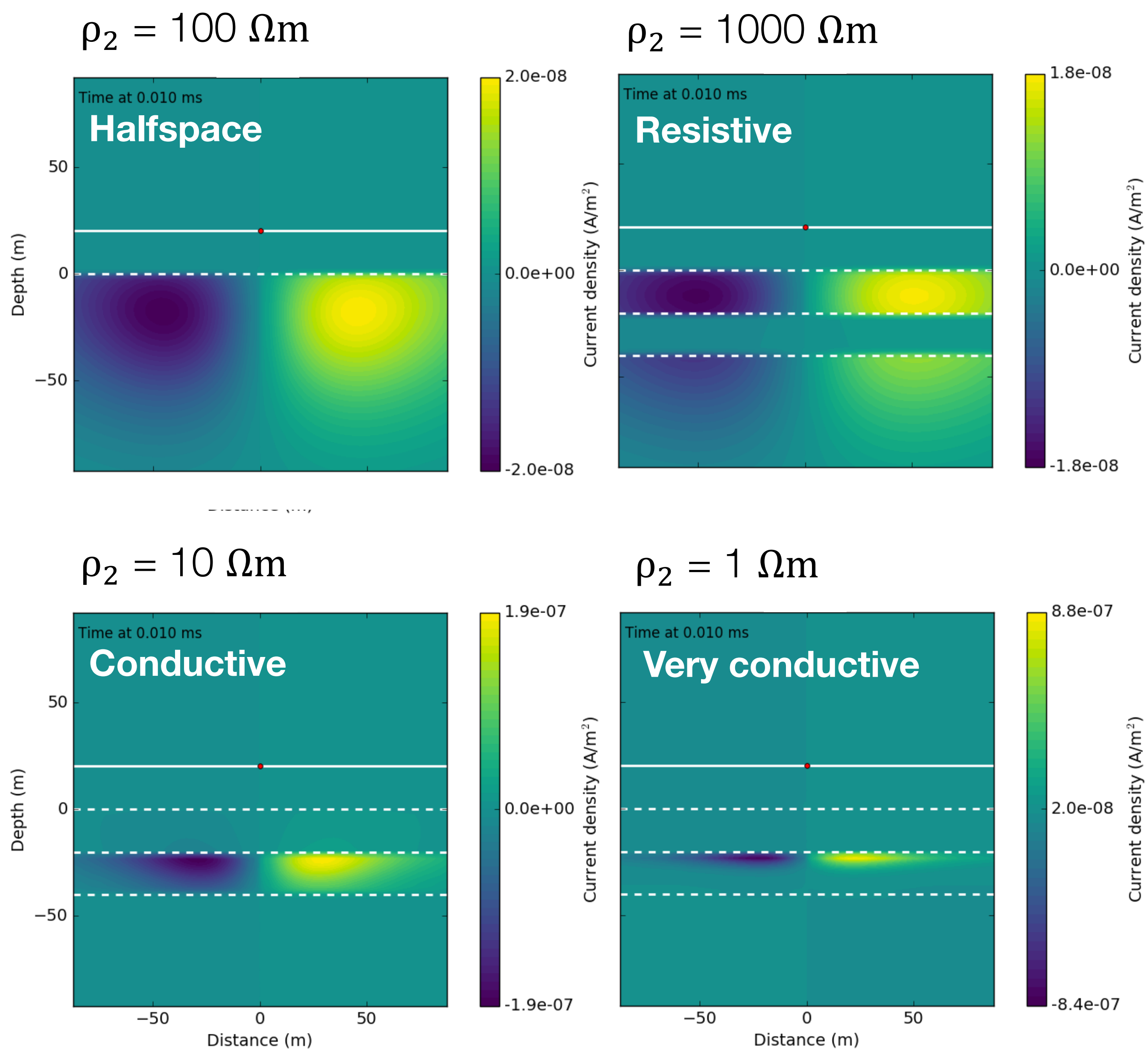
$\rho_2 = 1000\ \Omega\mathrm{m}$



$\rho_2 = 10\ \Omega\mathrm{m}$

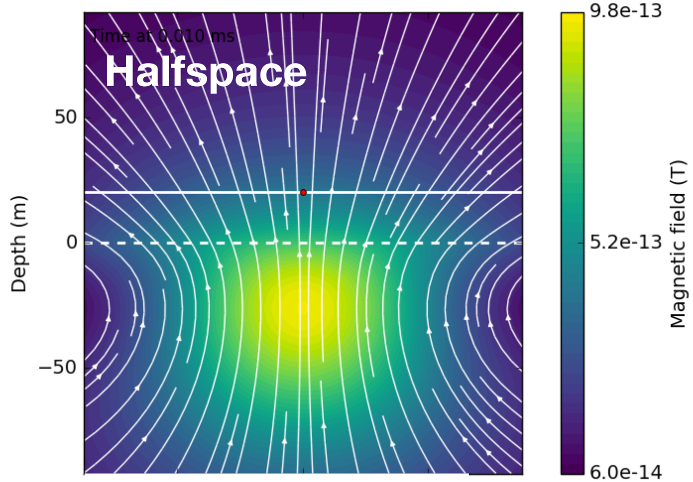


Layered earth currents (j_y)

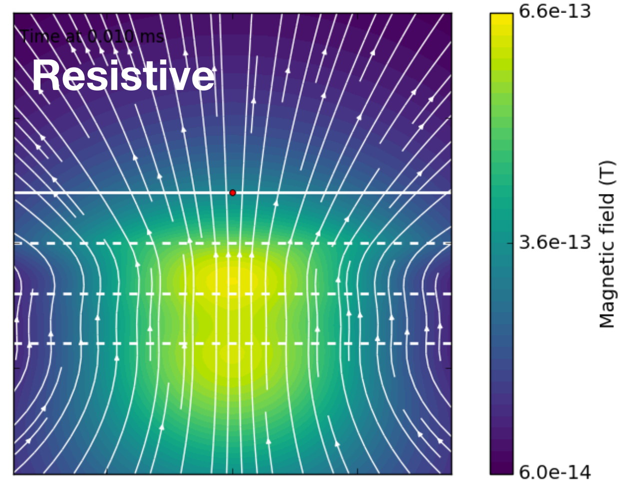


Layered earth mag. fields (**b**)

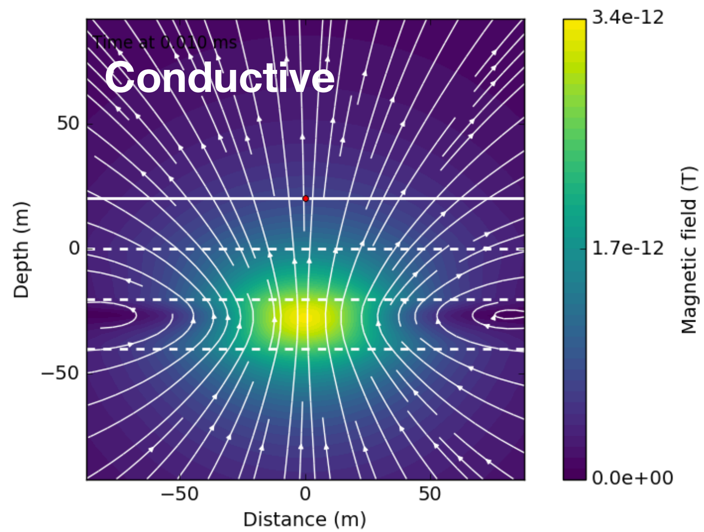
ρ_2 = 100 Ωm



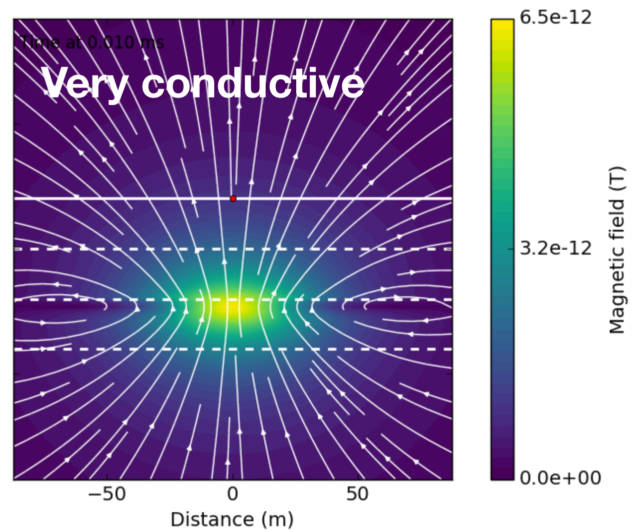
ρ_2 = 1000 Ωm



ρ_2 = 10 Ωm

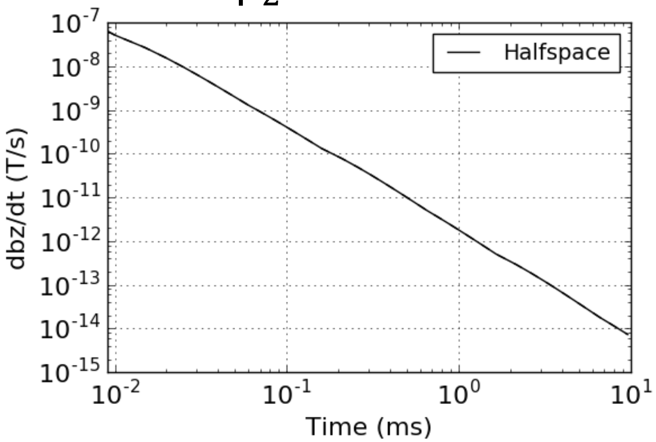


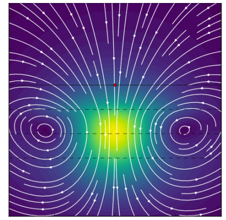
ρ_2 = 1 Ωm



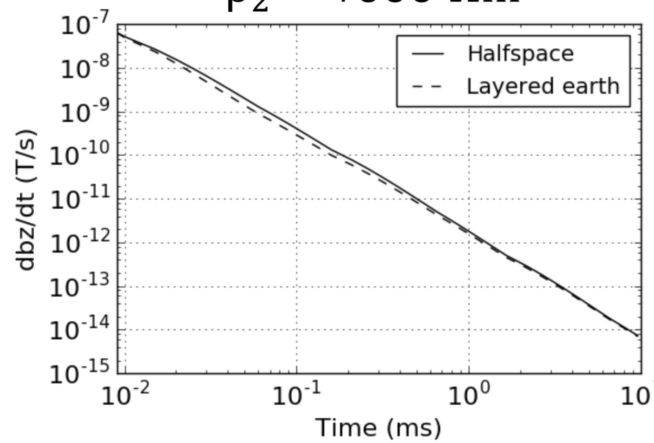
db_z/dt sounding curves

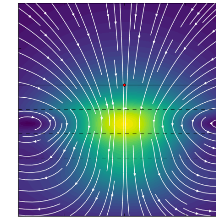
ρ_2 = 100 Ωm



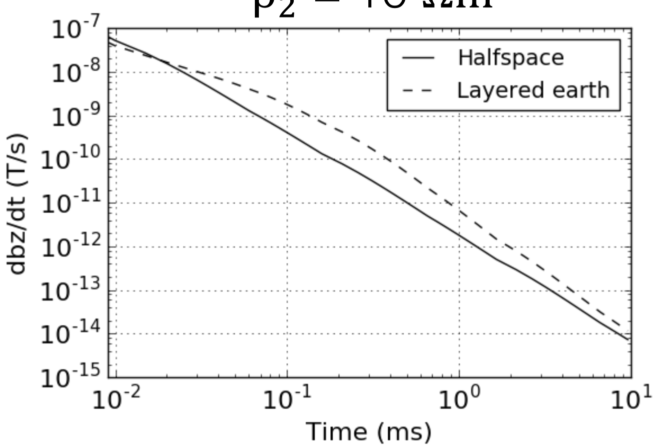


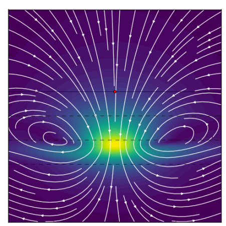
ρ_2 = 1000 Ωm



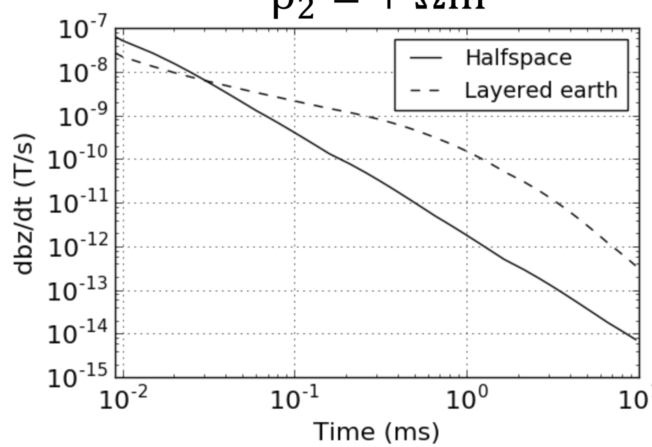


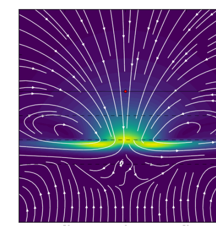
ρ_2 = 10 Ωm





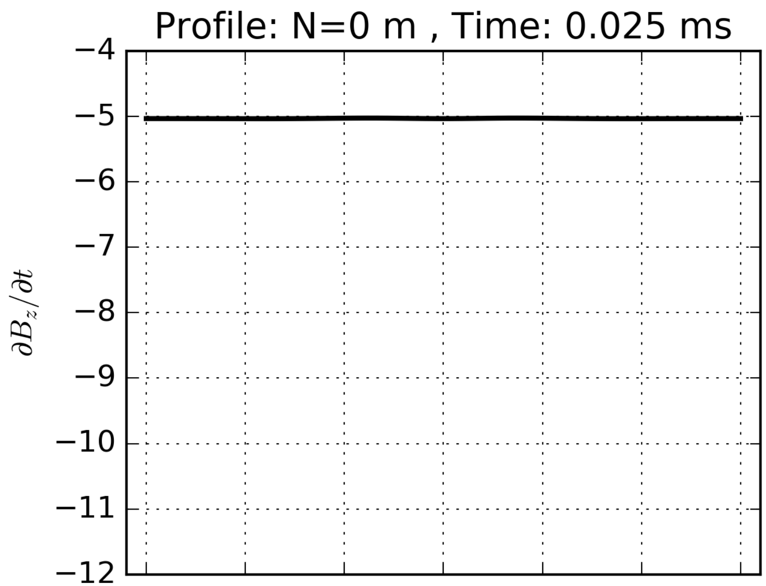
ρ_2 = 1 Ωm



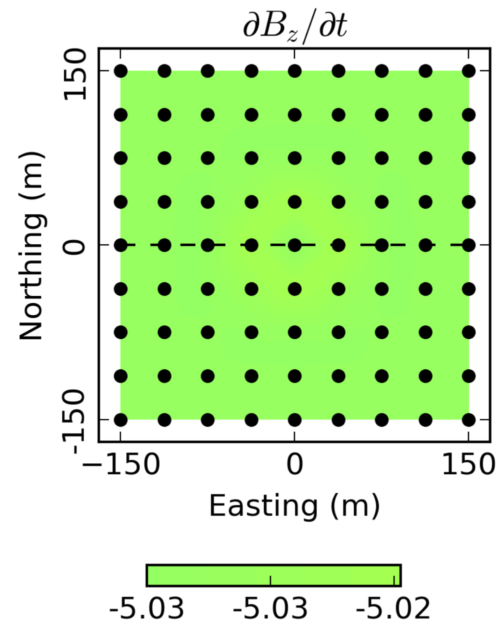


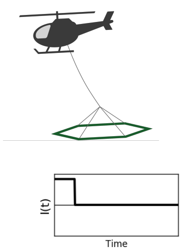
Airborne example: conductive sphere

Data profile

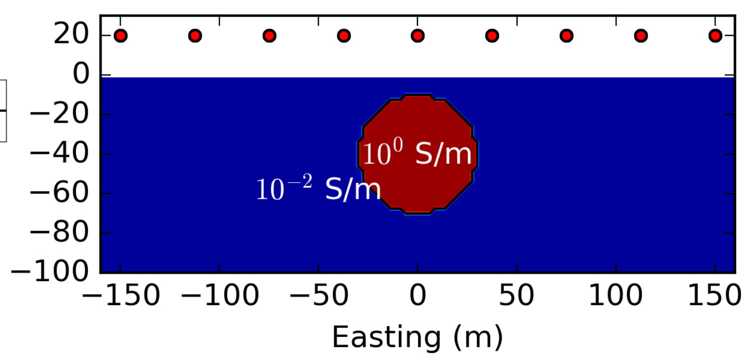


Data map



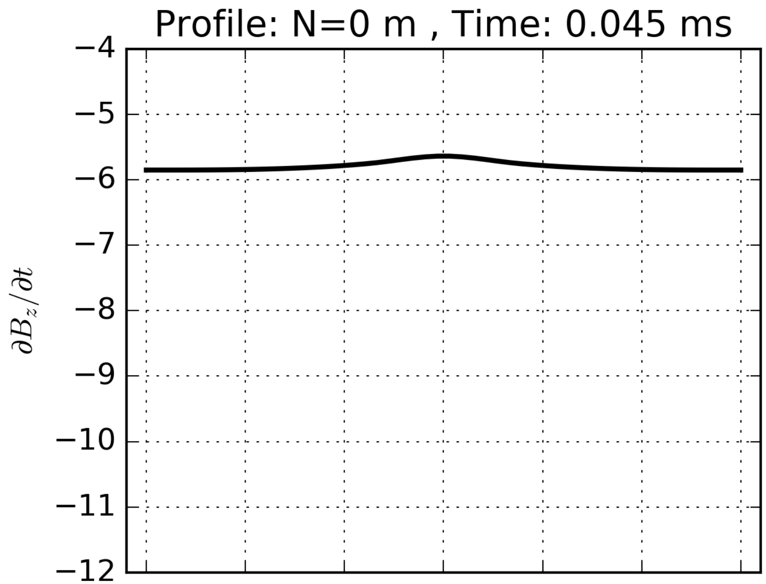


Conductivity

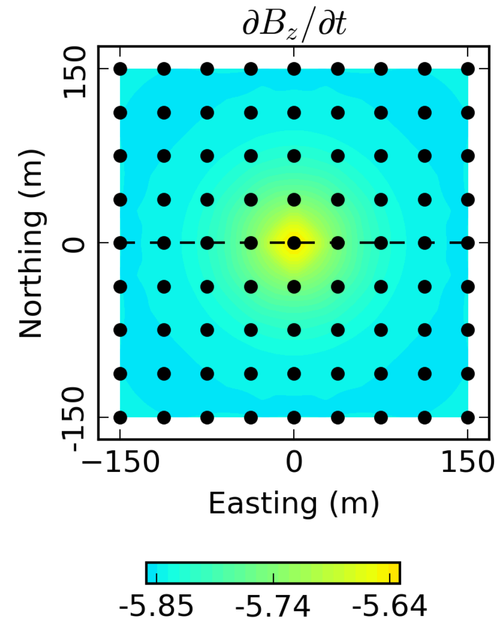


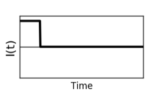
Airborne example: conductive sphere

Data profile

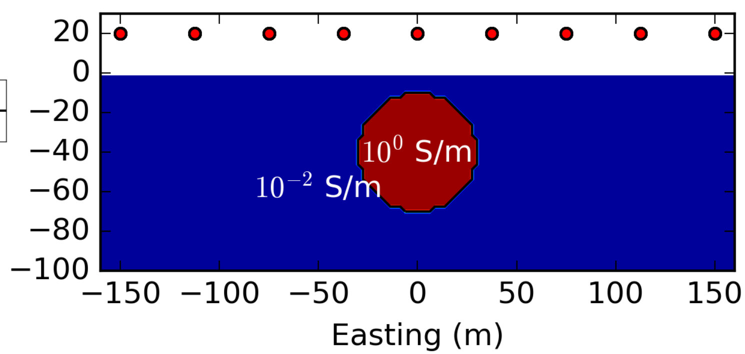


Data map



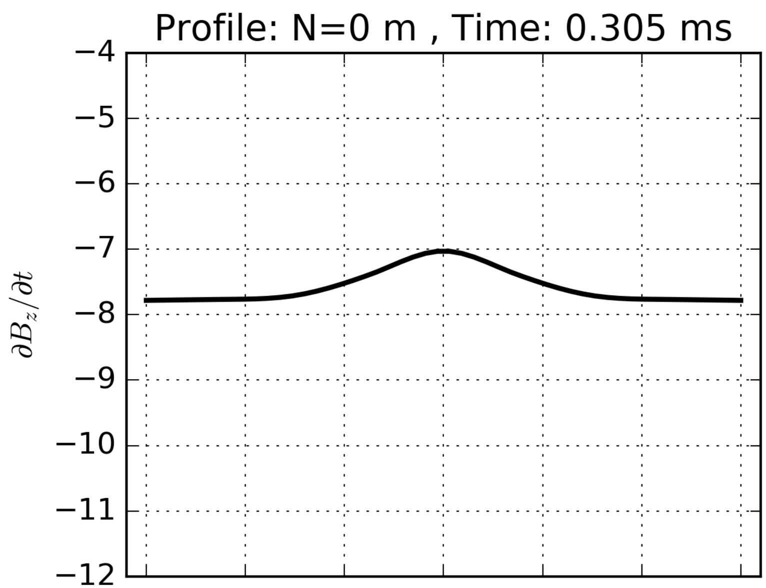


Conductivity

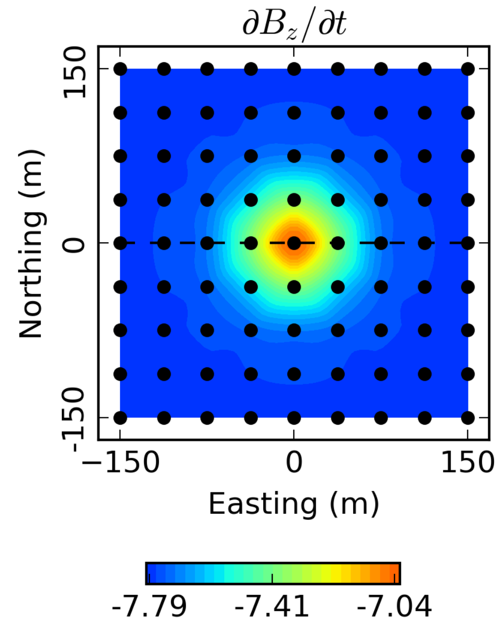


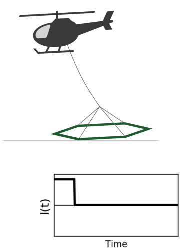
Airborne example: conductive sphere

Data profile

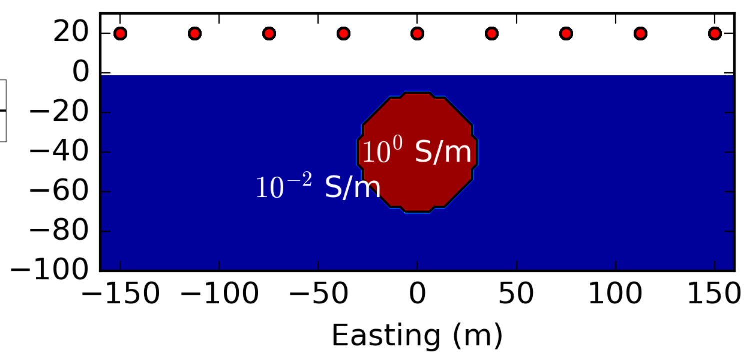


Data map



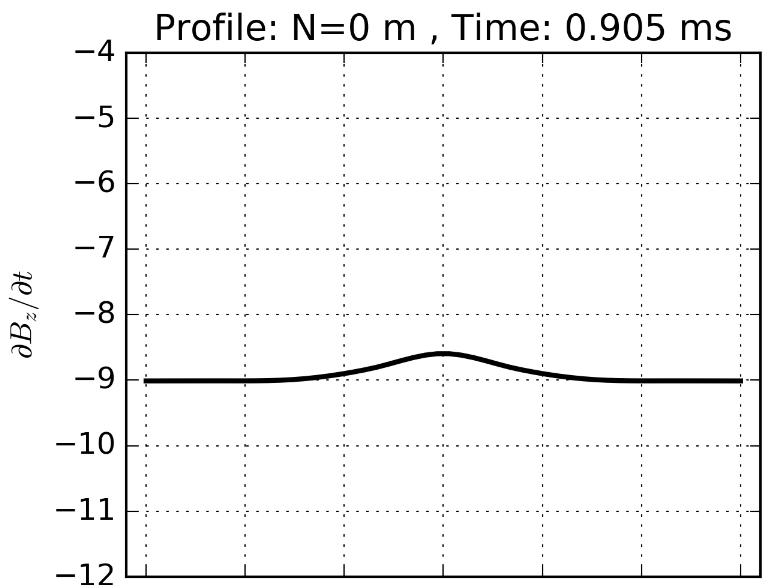


Conductivity

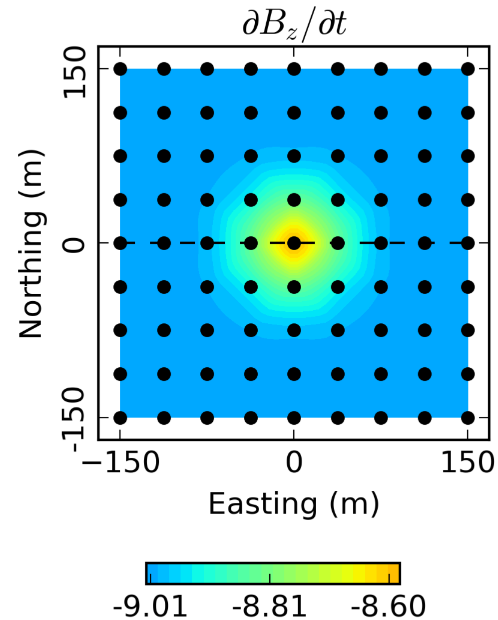


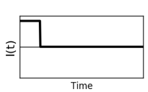
Airborne example: conductive sphere

Data profile

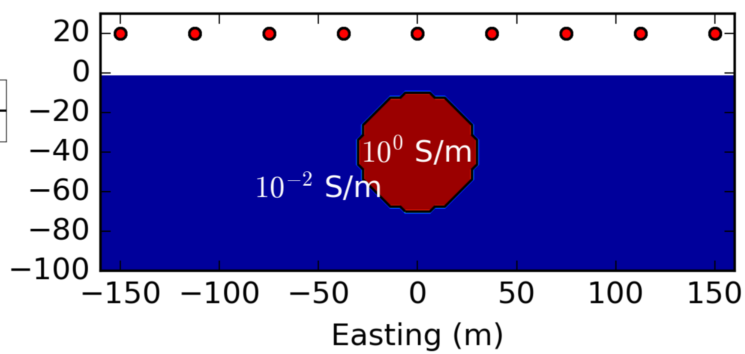


Data map



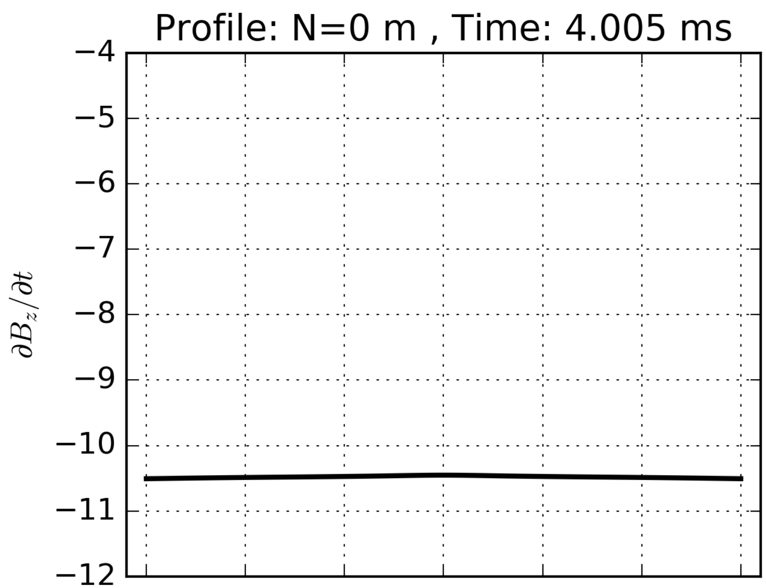


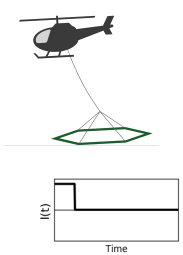
Conductivity



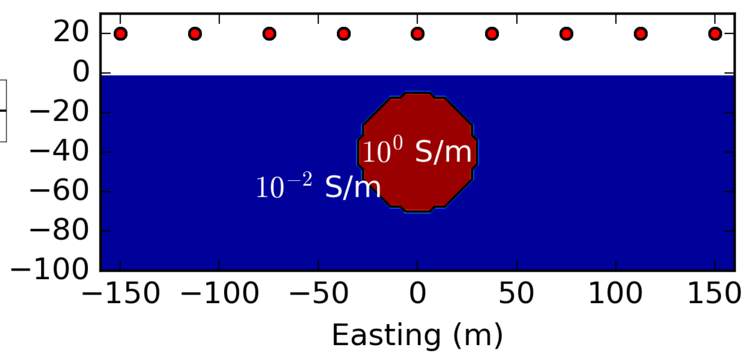
Airborne example: conductive sphere

Data profile

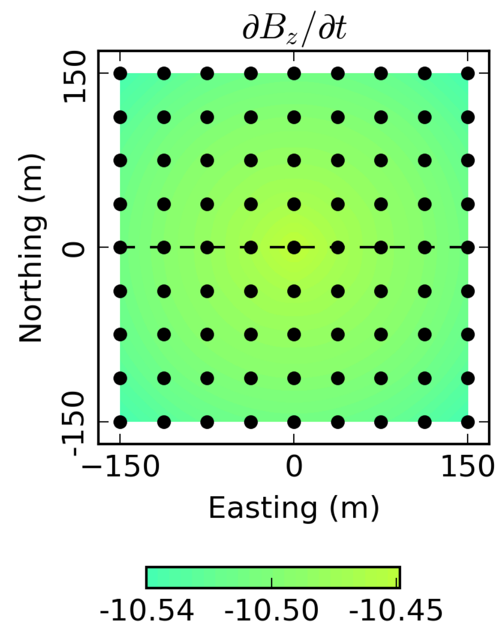




Conductivity

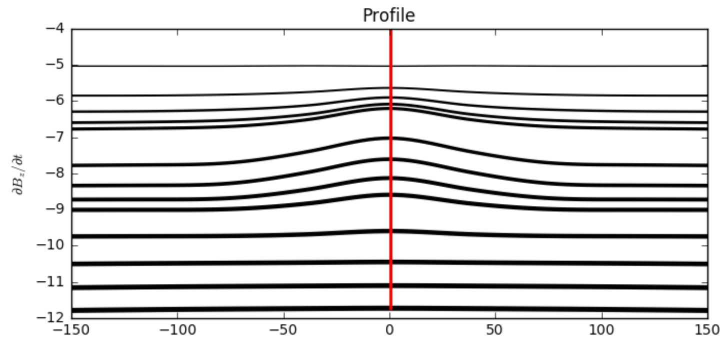


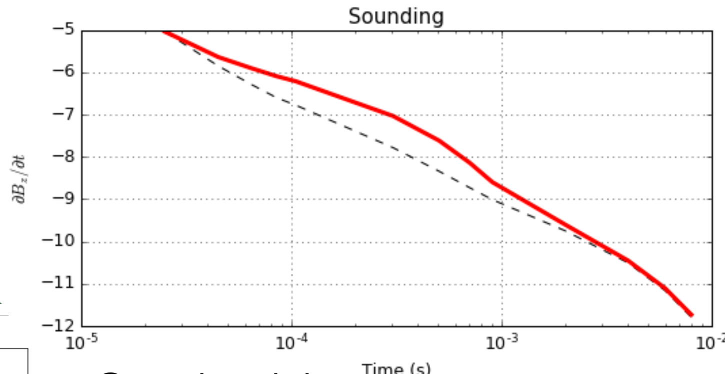
Data map

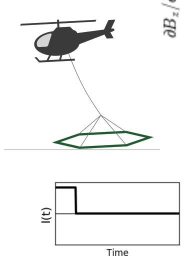


Summary: airborne example

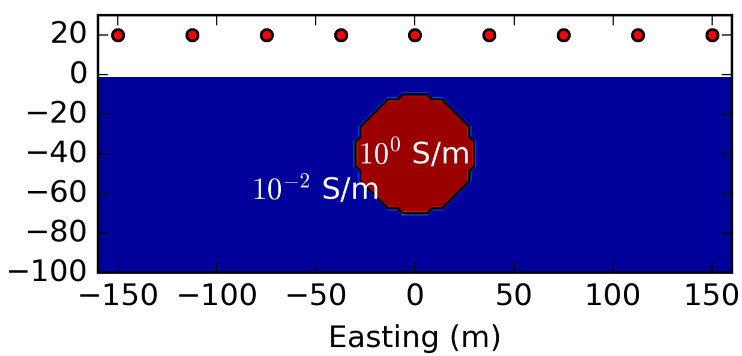
Data profile



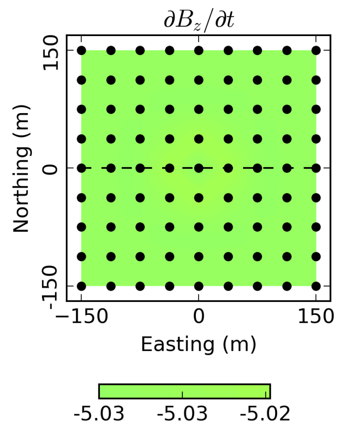




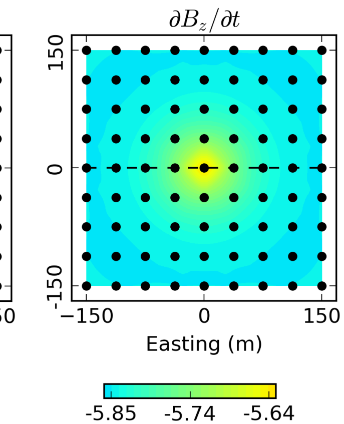
Conductivity



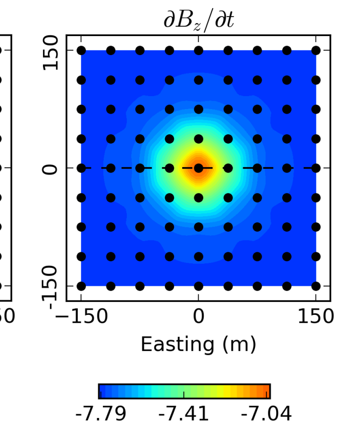
0.025 ms



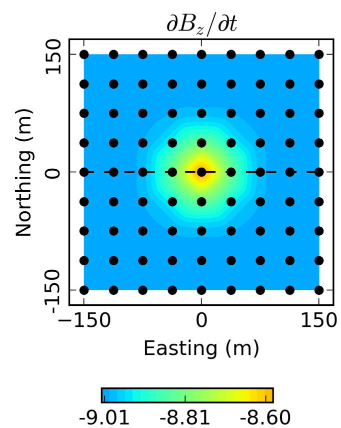
0.045 ms



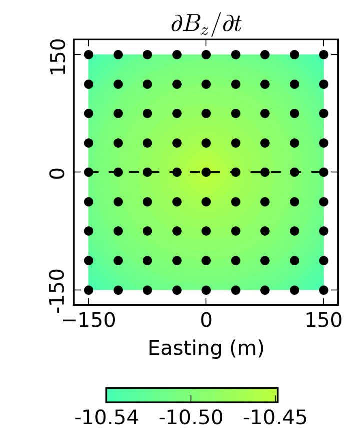
0.305 ms



0.905 ms

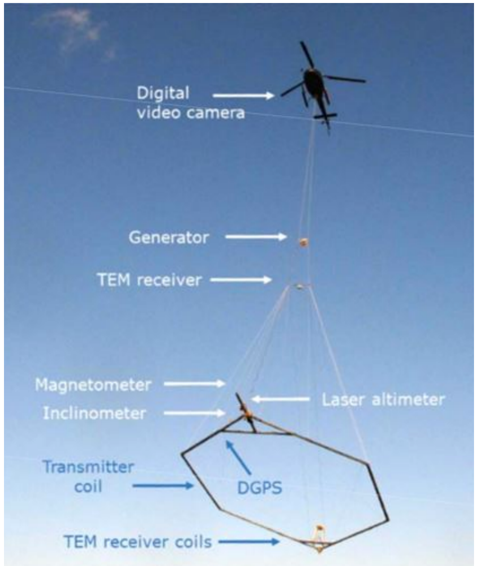


4.005 ms



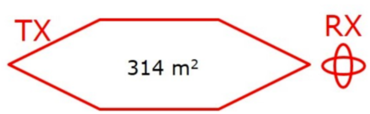
Some Airborne TDEM Systems

SkyTEM (2006)

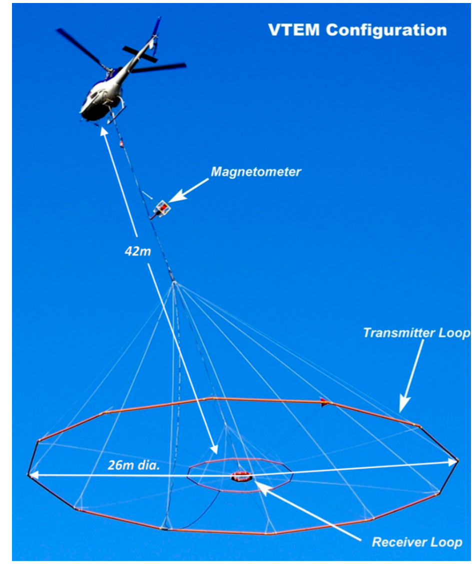


Area = 314 m^2

Peak dipole moment:
- HM: 113040 NIA
- LM: 12560 NIA

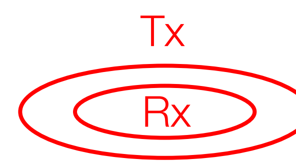


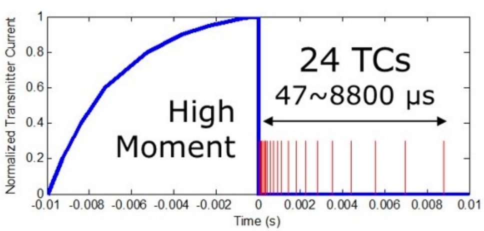
VTEM (2007)



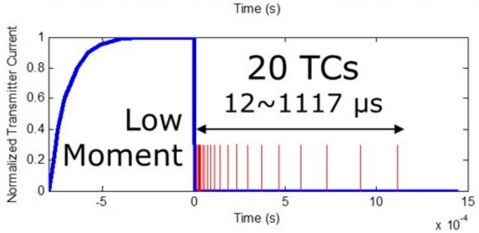
Area = 535 m^2

Peak dipole moment:
- 503,100 NIA

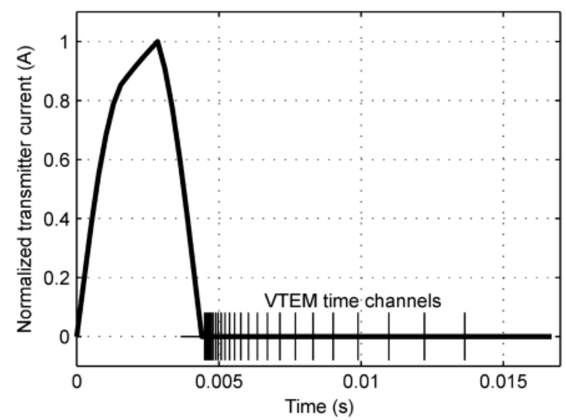




Peak current: 90 A
Turns: 4
On-time: 10 ms
Off-time: 10 ms



Peak current: 40 A
Turns: 1
On-time: 0.8 ms
Off-time: 1.45 ms



Peak current: 235 A
Turns: 4
On-time: 4.5 ms
Off-time: 9.1 ms

Outline

Setup

Time Domain EM

- Vertical Magnetic Dipole
- Propagation with Time
- Effects of Background Conductivity
- Transmitters and receivers
- Decay Curves
- Case History: Groundwater, Minerals

Frequency Domain EM

Questions

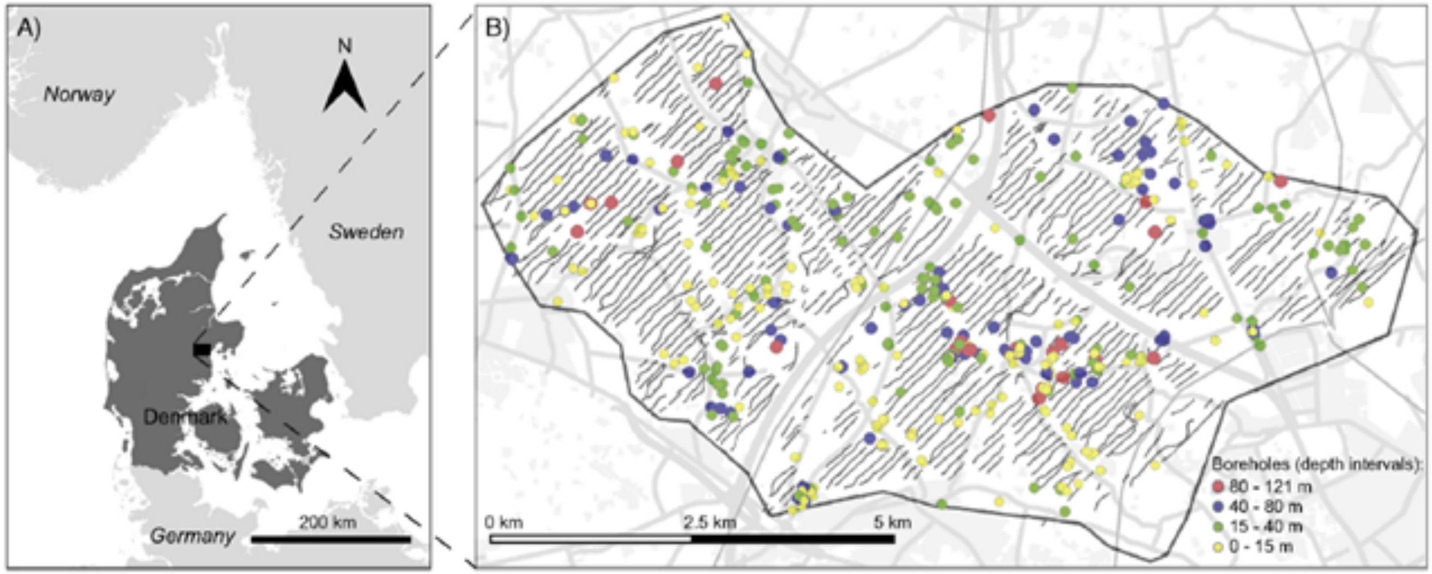
Case History: Kasted

Vilhelmsen et al. (2016)

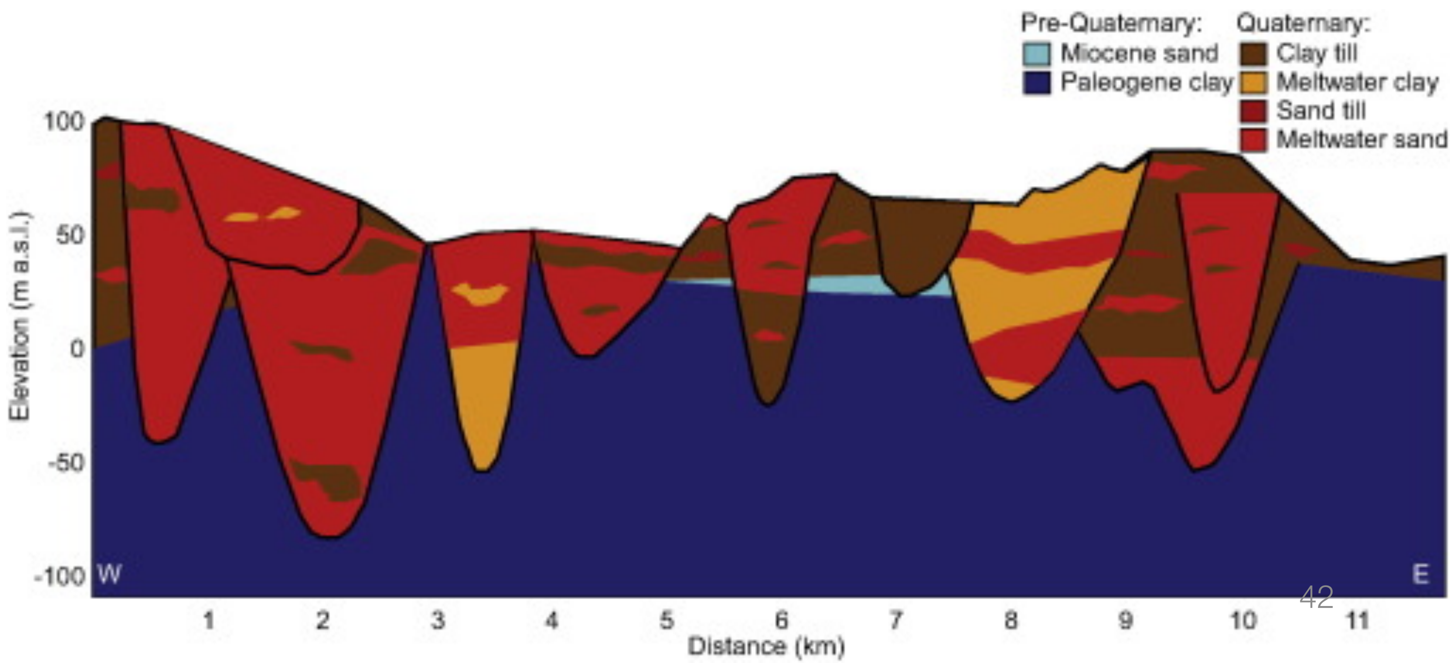
Setup

A) Survey Area: Kasted, Demark

B) Borehole locations

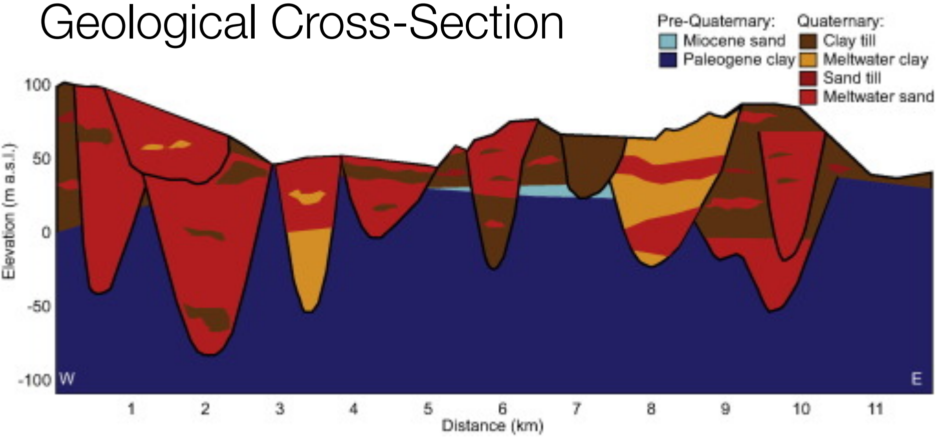


Local Geology: W-E cross-section



Properties

Geological Cross-Section

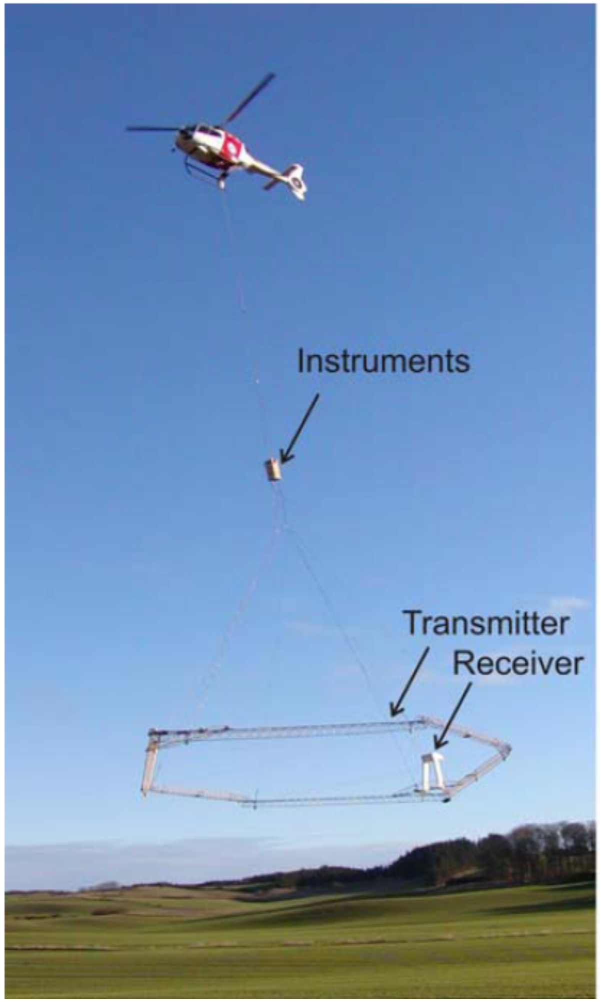


Geological Units	Resistivity (Ωm)
Palaeogene Clay	1-10
Clay Till	25-60
Sand Till	>50
Meltwater Sand and Gravel	>60
Glaciolacustrine Clay	10-40
Miocene Silt and Sand	>40
Miocene Clay	10-40
Sand	>40
Clay	1-60

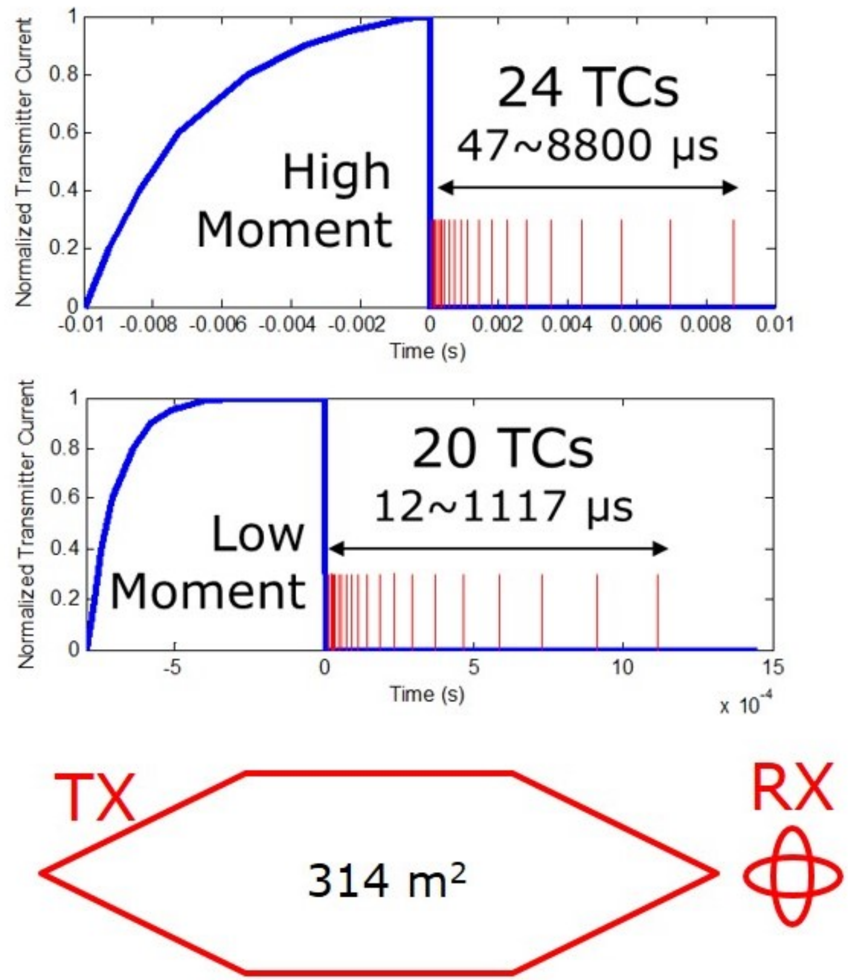
- Buried valleys with clays beneath
- Infill (water-bearing): coarse sand and gravel
- Clays are conductive (1-40 Ωm)
- Water-bearing sands and gravels are more resistive (>40 Ωm)

Survey

SkyTEM System



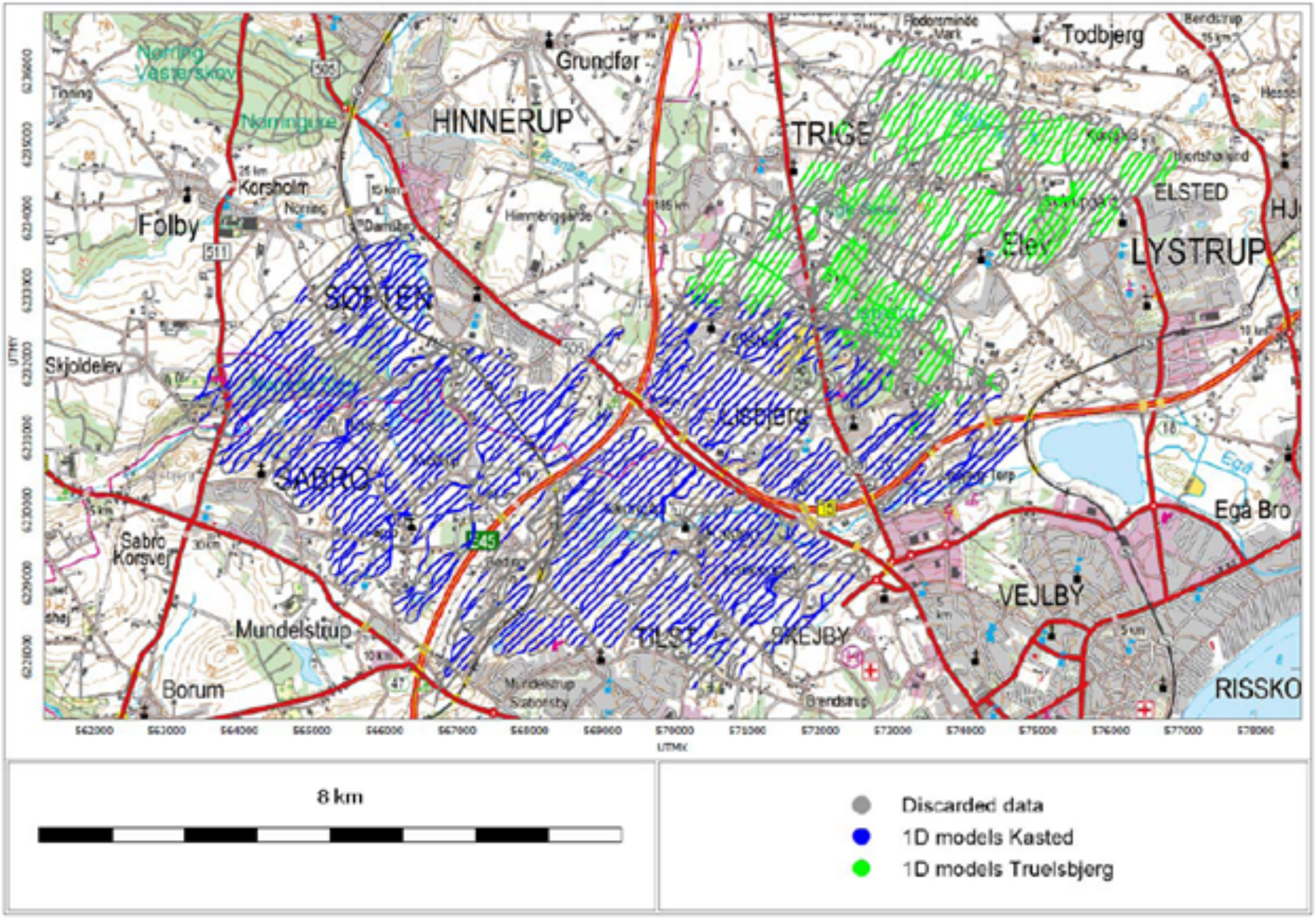
System Configuration



- Low moment (LM) used to image near surface structures
- High moment (HM) used to image deeper structures

Data

Blue: data used for Kasted study



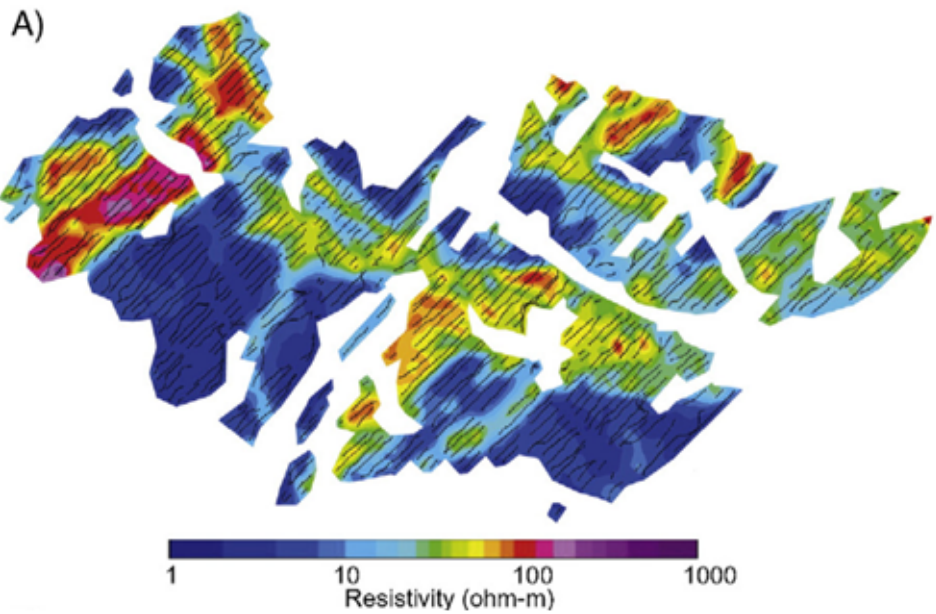
- 333 line km of data, 100 m line-spacing
- Data points with strong coupling to cultural noise were removed (~30%)

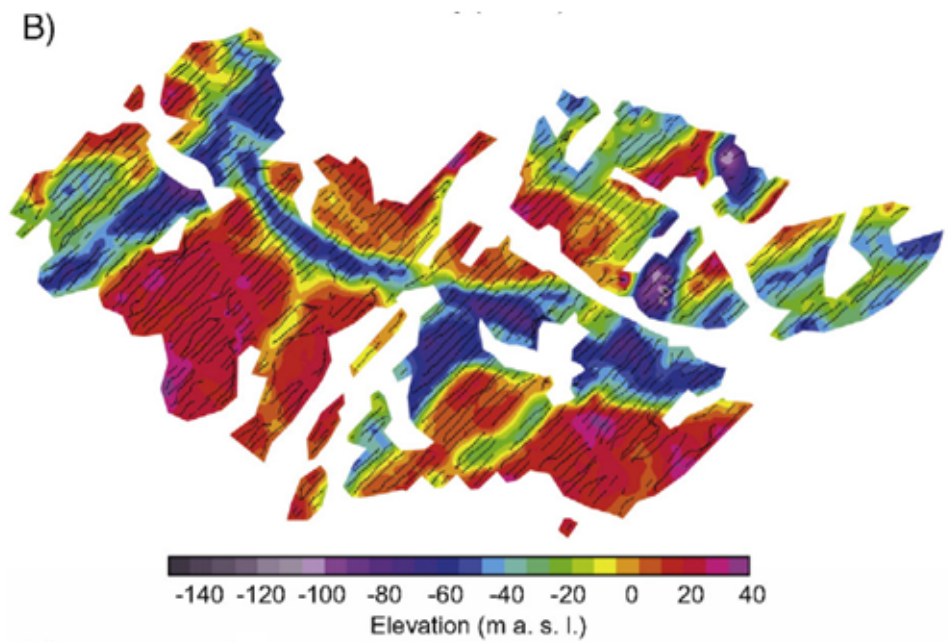
Processing (inversion)

- Spatially constrained 1D inversion → quasi-3D approach
- 9,500 soundings were inverted using 25 layers

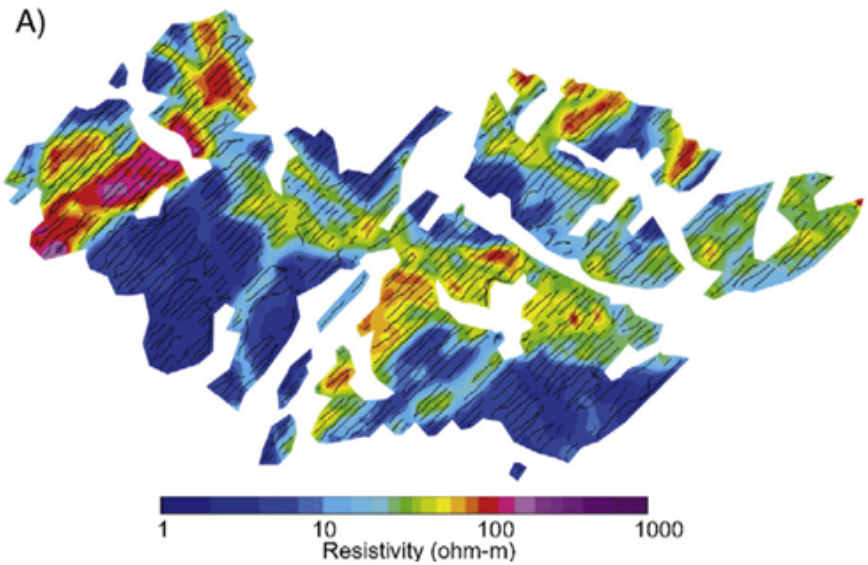
Depth slice 5 m above sea-level

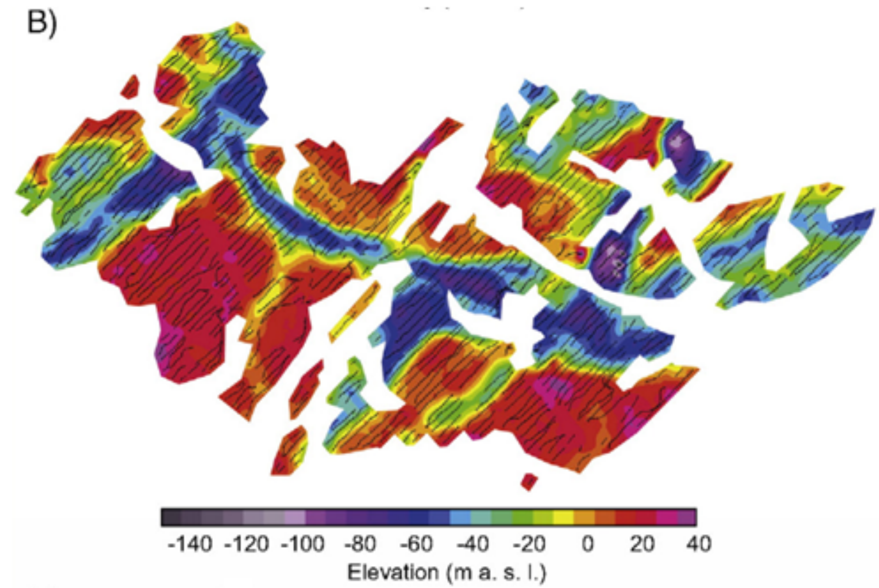
Approximate depth to the top of Paleogene clay layer



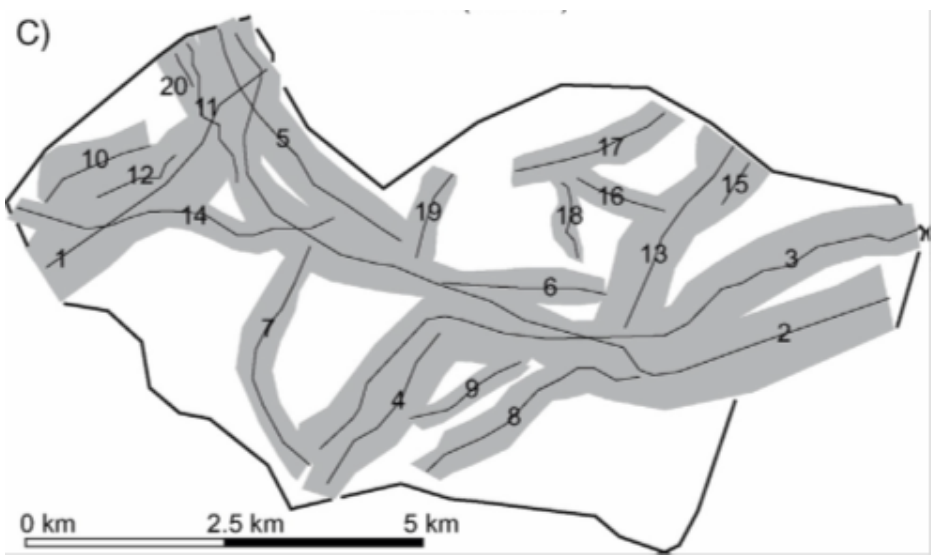


Interpretation



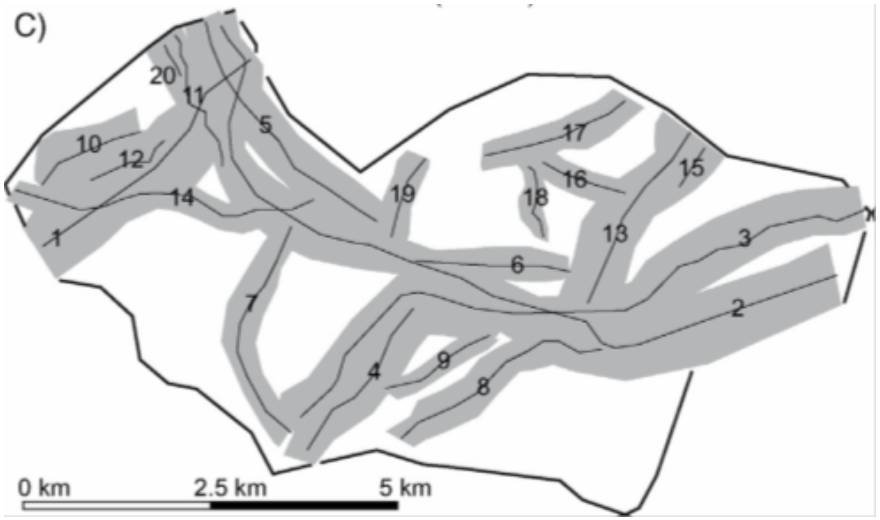


Delineation of valley structures

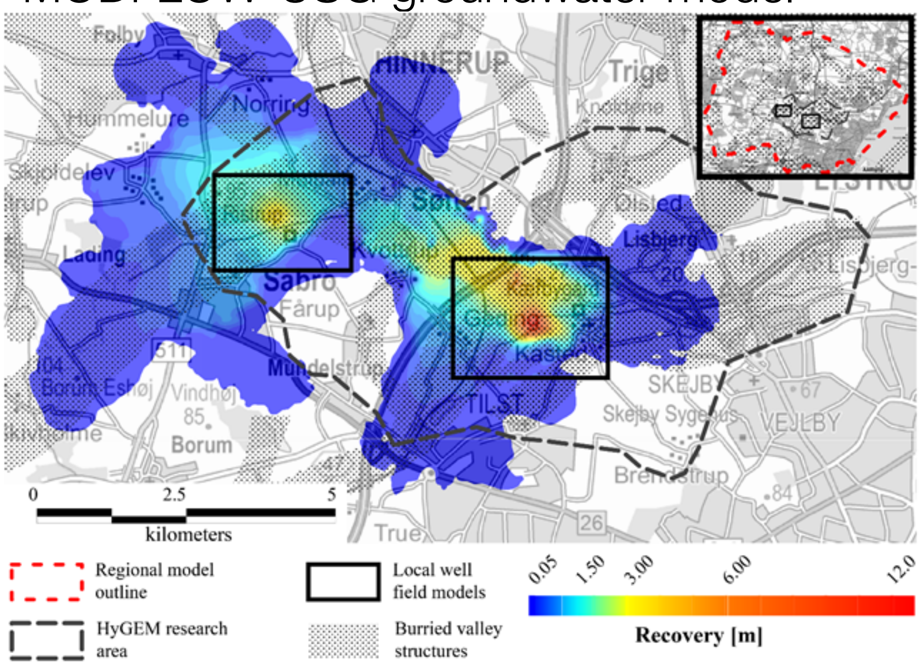


- Inversion results used to construct geological model.
- Delineated 20 buried and cross-cutting valley structures.

Synthesis



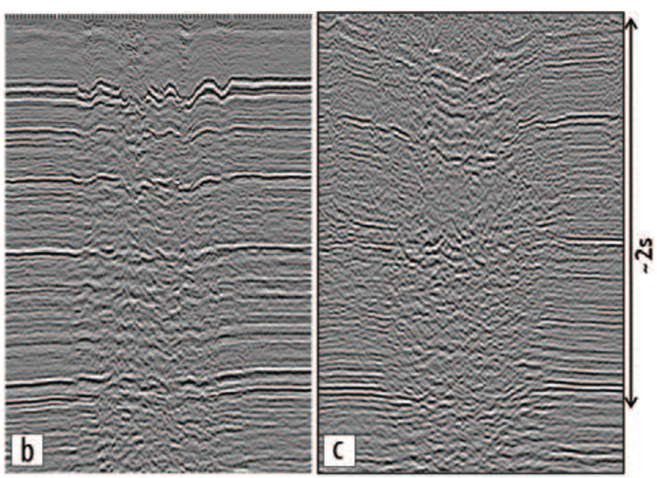
MODFLOW-USG groundwater model

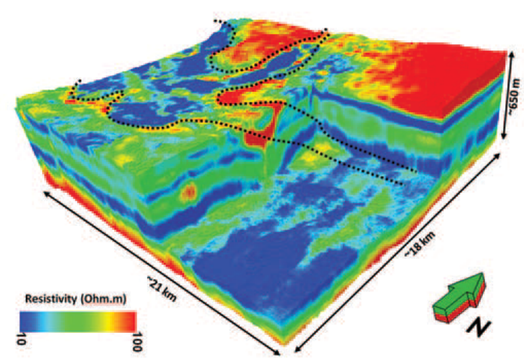


- 3D geologic model incorporated into MODFLOW-USG groundwater modeling tool
- Extracted water from 2 wells.
- Downdraw between the two wells correlated with the resistive valley structures

Case History: Wadi Sahba

Colombo et al. 2016

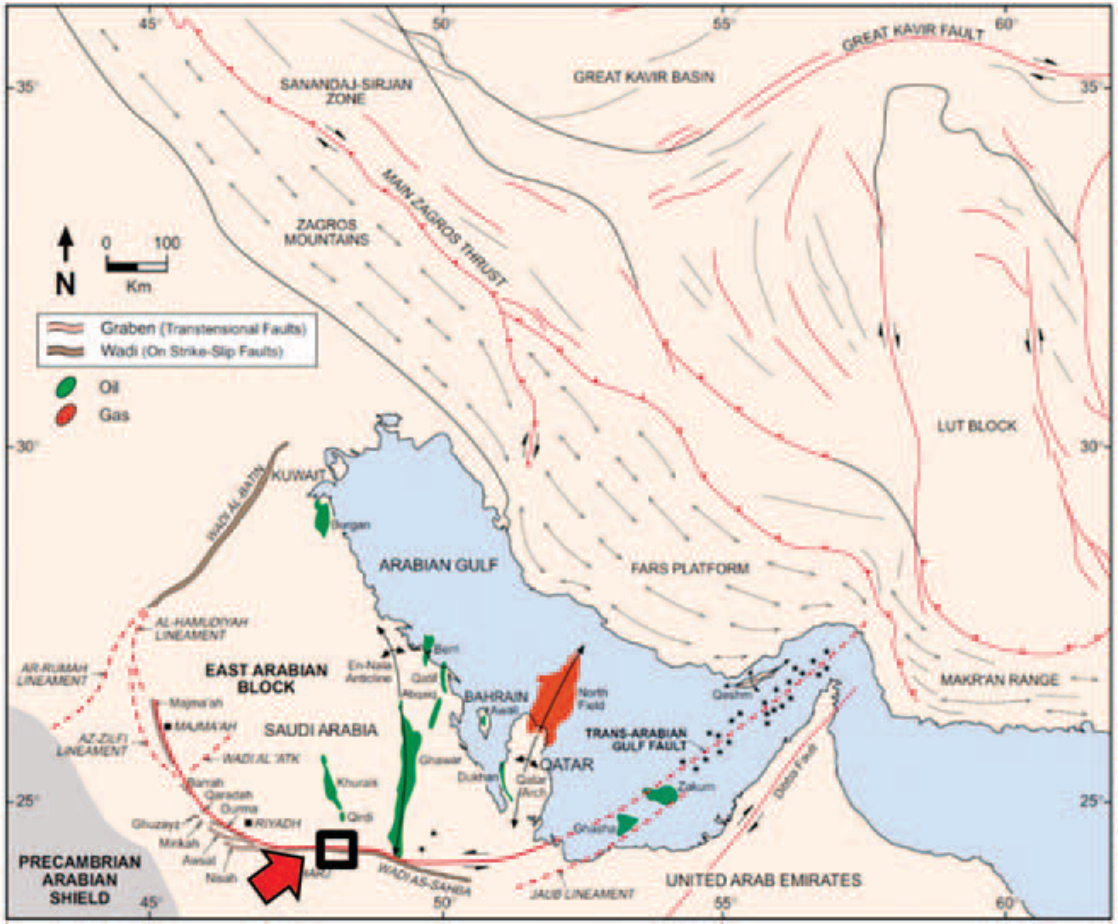




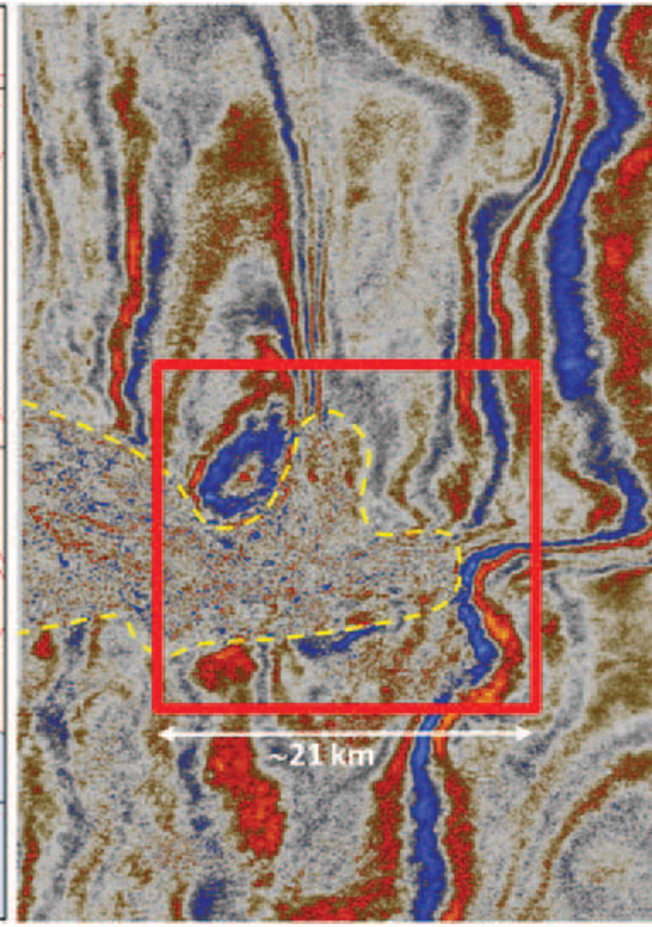
?

Setup

Location of Wadi area, Saudi Arabia



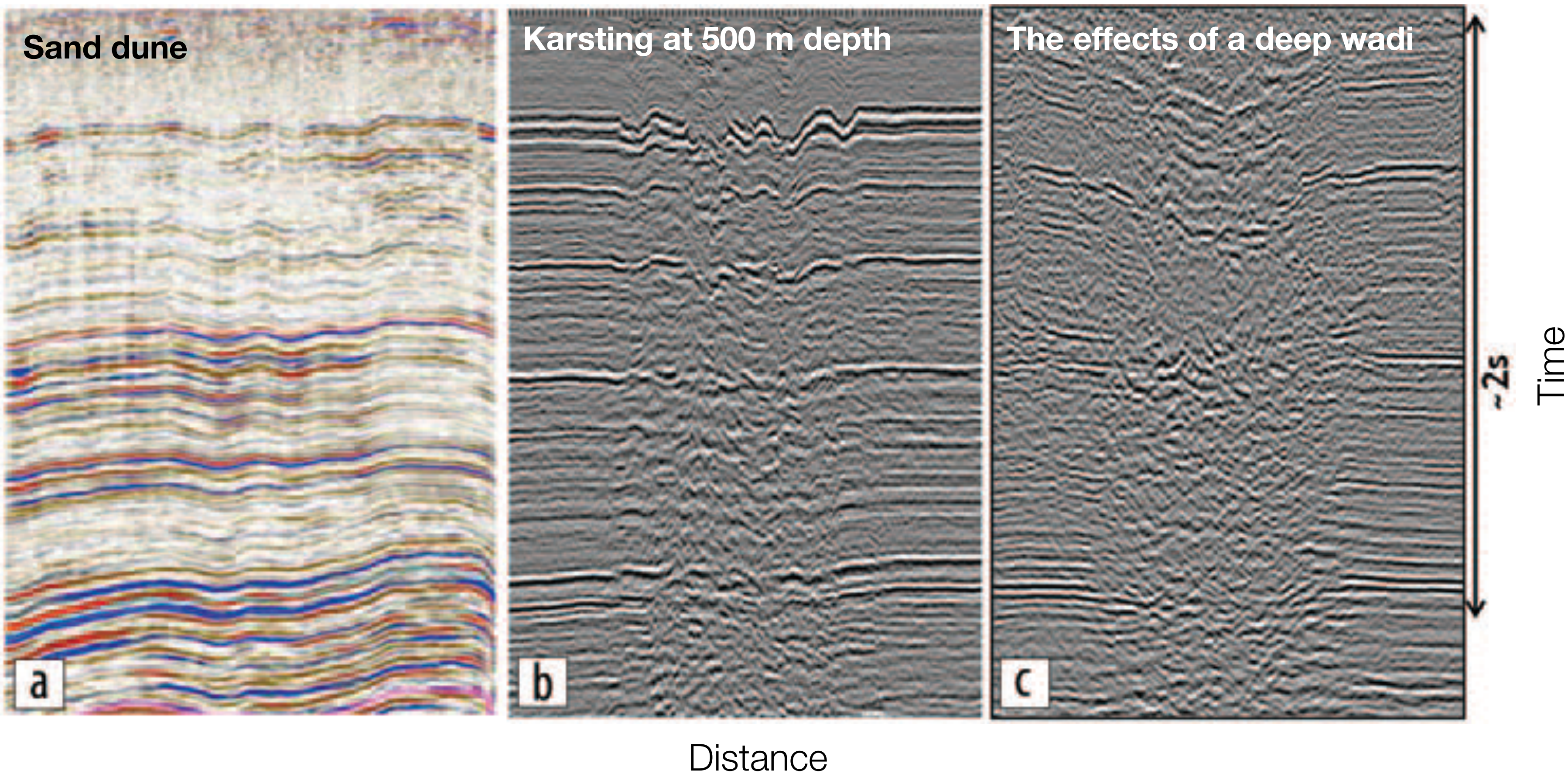
Seismic slice



- Oil and gas exploration in the Middle East: Focus is now stratigraphic traps and low relief structures

Challenges for processing seismic data

Example seismic sections



- Strong effects from near surface anomalies even after static corrections

Properties

- P-velocity and conductivity:

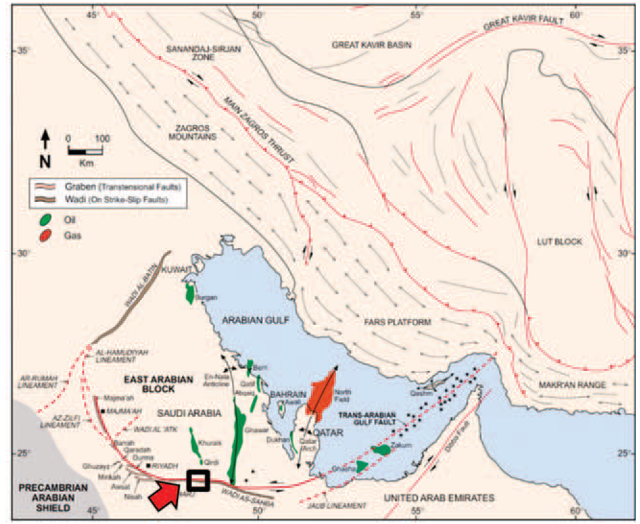
$$v_p = g(\phi)$$
$$\sigma = f(\phi)$$

v_p: P-velocity
ϕ: porosity

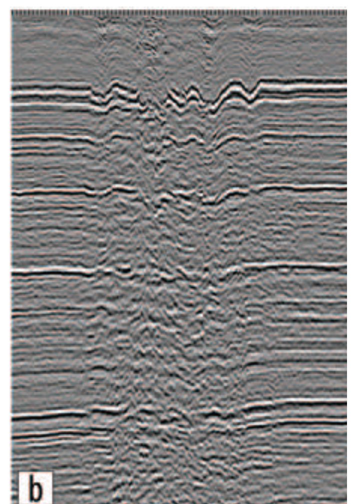
- Poor seismic data:
  - strong scattering effects probably caused by flower faults
  - velocity inversions (high to low v_p)

- From previous multi-physics analyses:
  - strong structural similarity between the inverted resistivity, and the existing seismic results

Geologic map



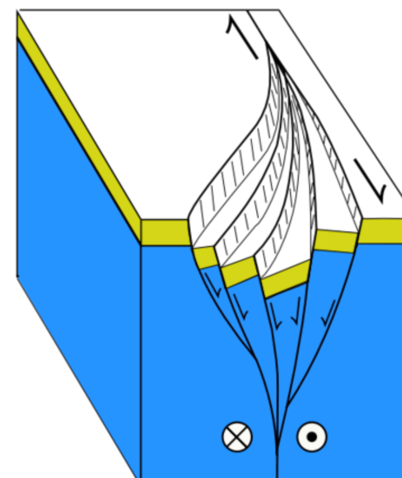
Seismic section



Time

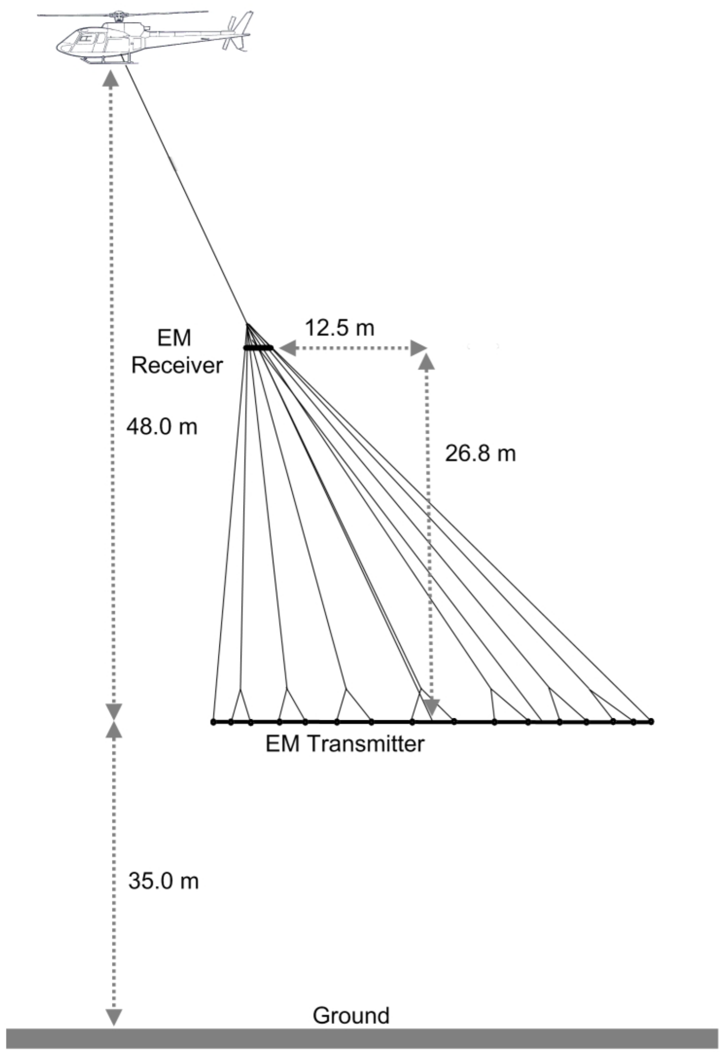
Distance

Flower faults

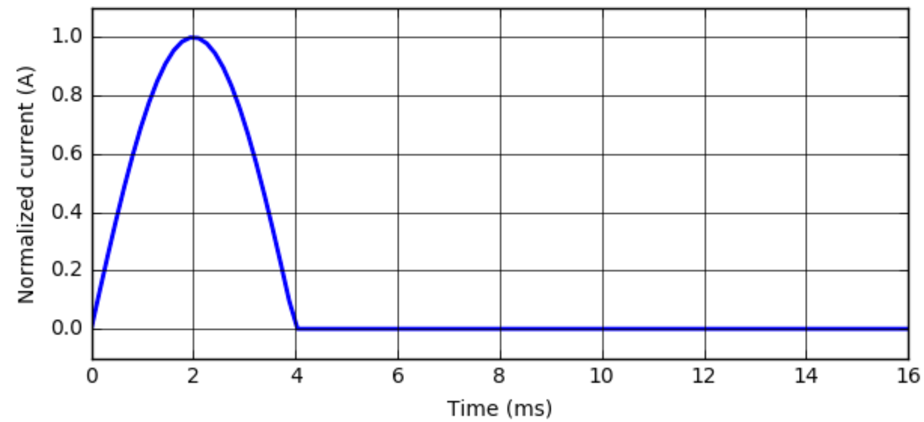


Survey

HELITEM

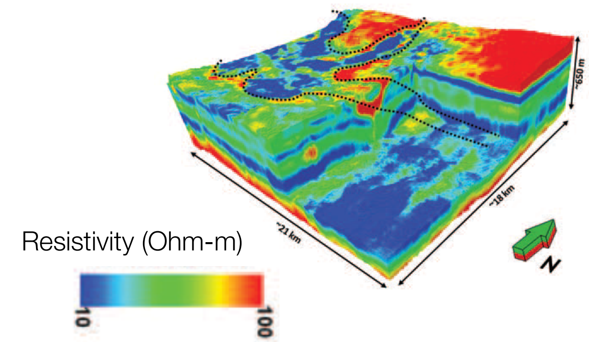


System Configuration

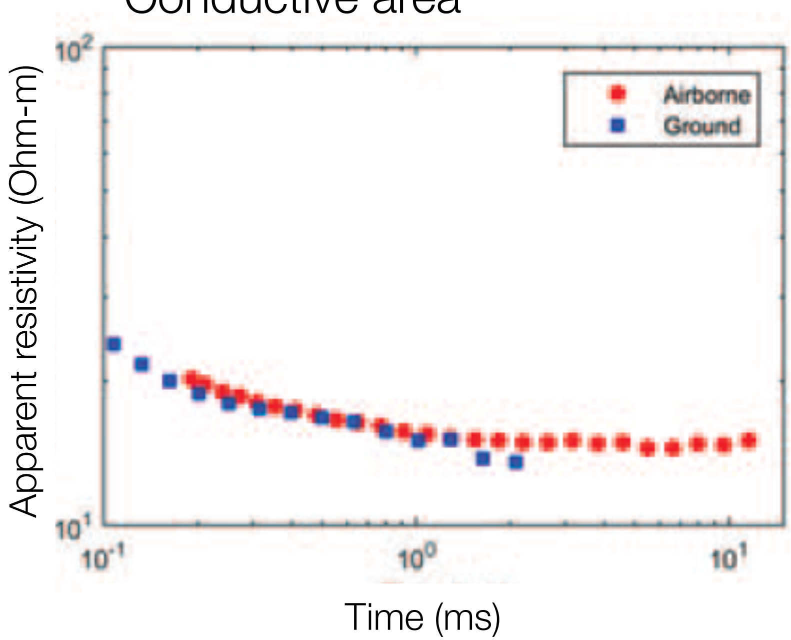


- Peak Tx current: 1200 A
- Dipole moment: 1.7×10^6 A-m^2
- Stacked TEM curve spacing: ~2.7 m
- Total soundings: ~1.6 million

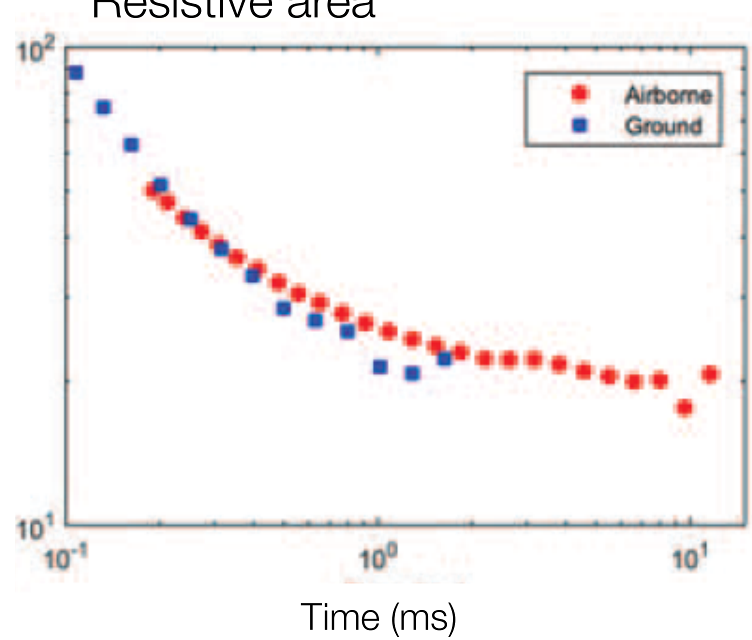
Comparisons: airborne and ground EM



Conductive area

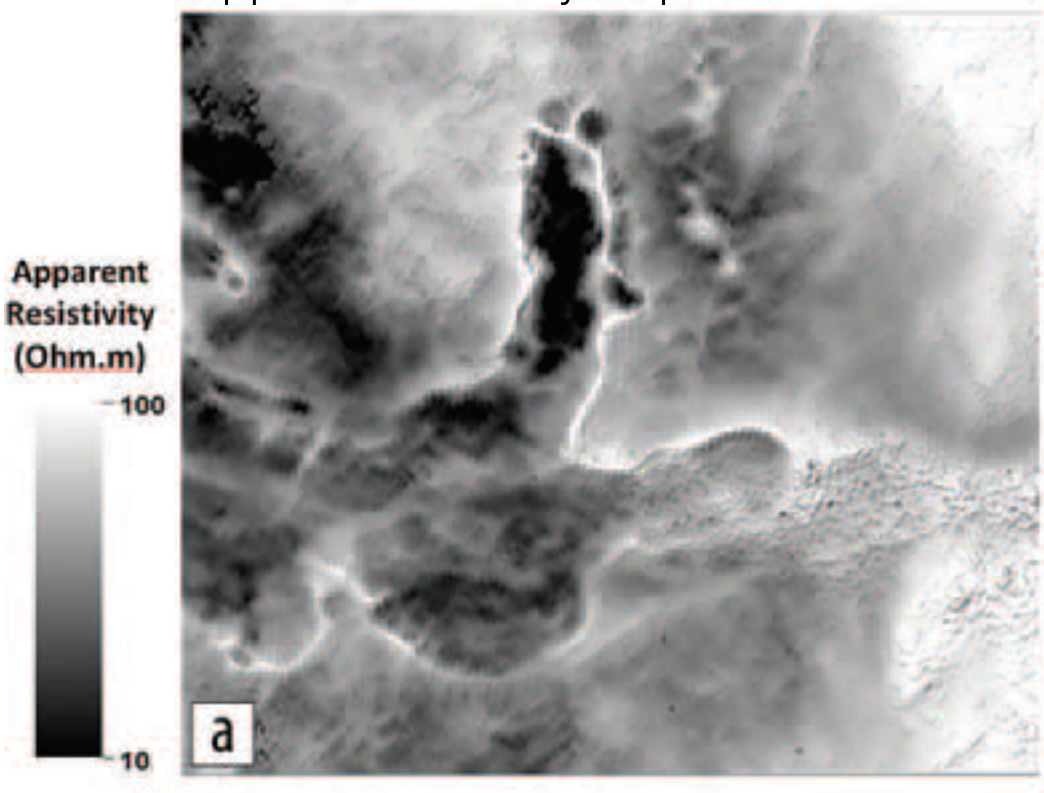


Resistive area



EM data

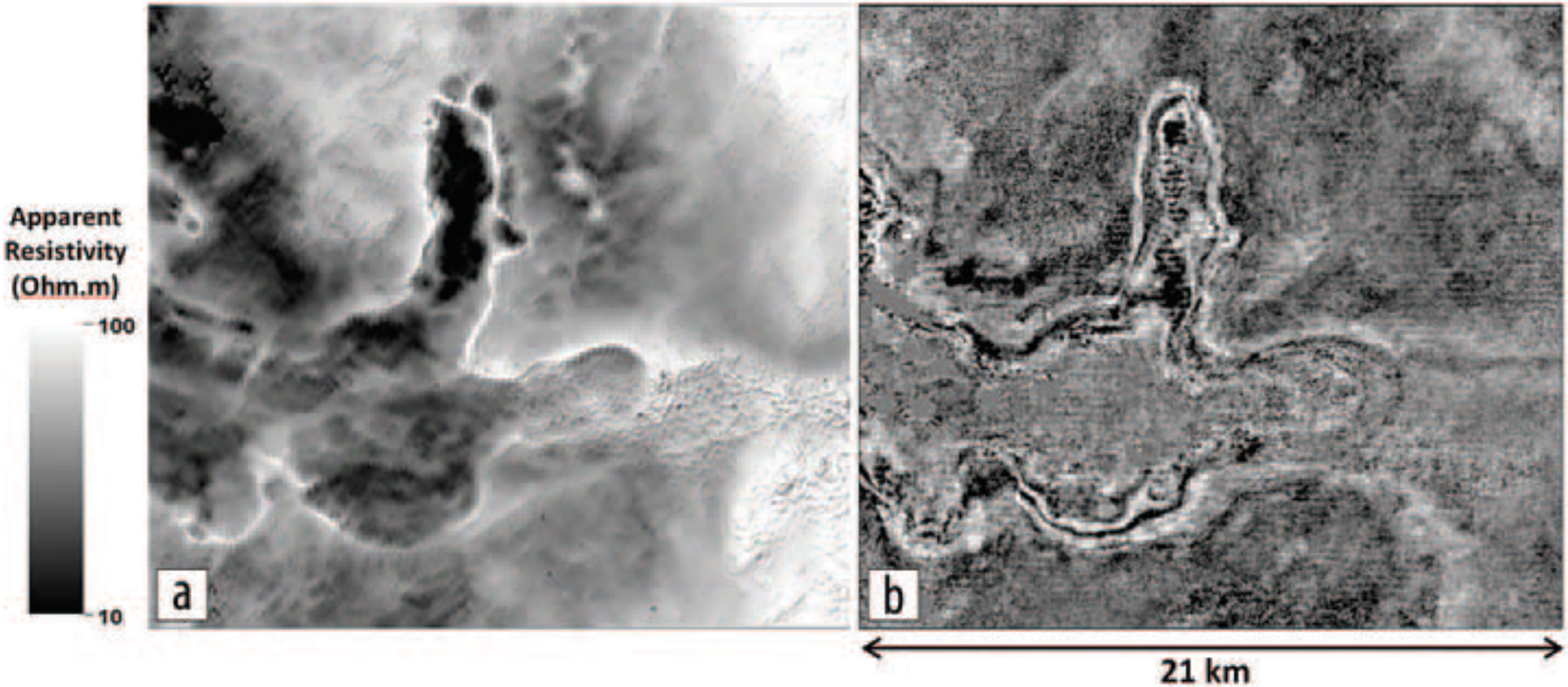
Apparent resistivity map



Comparison: EM and Seismic data

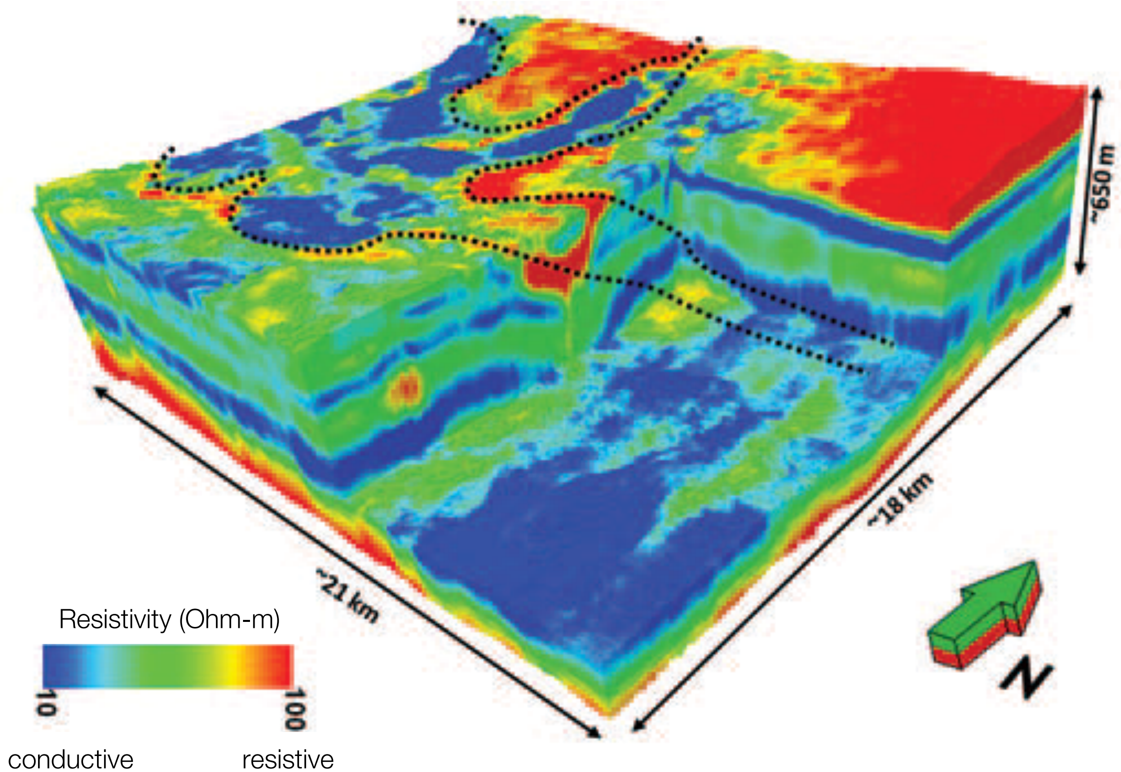
Apparent resistivity map

Seismic time slice



Processing: EM inversion

Conductivity model



- 1D inversion for each sounding location
- Lateral constraint is used

Cooperative inversion: Seismic + EM

- How **EM** can help seismic tomography inversion?

Velocity (v_p): high to low (significant challenge)

Conductivity ($\boldsymbol{\sigma}$): high to low

$$v_p = g(\phi)$$
$$\sigma = f(\phi)$$

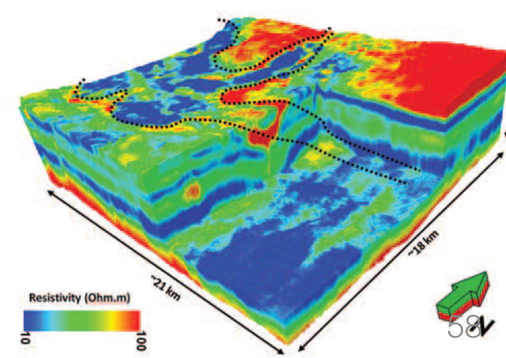
ϕ: porosity

$\mathbf{m}_s$: Slowness
$\mathbf{m}_\sigma$: Conductivity

$$\psi(\mathbf{m_s}, \mathbf{m}_\sigma) = \psi_m(\mathbf{m}_s) + \frac{1}{\lambda_1}\psi_d(\mathbf{m}_s) + \underline{\frac{1}{\lambda_2}\psi_x(\mathbf{m}_s, \mathbf{m}_\sigma)} + \frac{1}{\lambda_3}\psi_{rp}(\mathbf{m}_s, \mathbf{m}_\sigma)$$

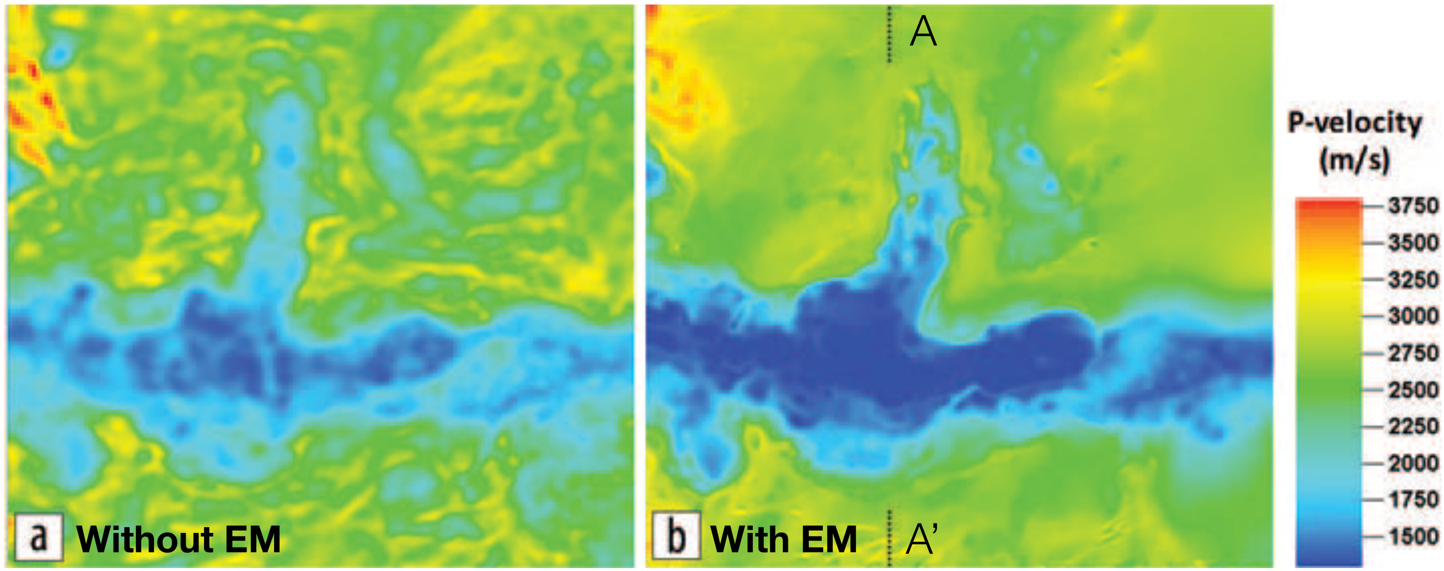
$$||\nabla \mathbf{m_s} \times \nabla \mathbf{m}_\sigma||_2^2$$

Gallardo and Meju, 2004



Cooperative inversion: Seismic + EM

V_p depth slices at 340 m below sea level

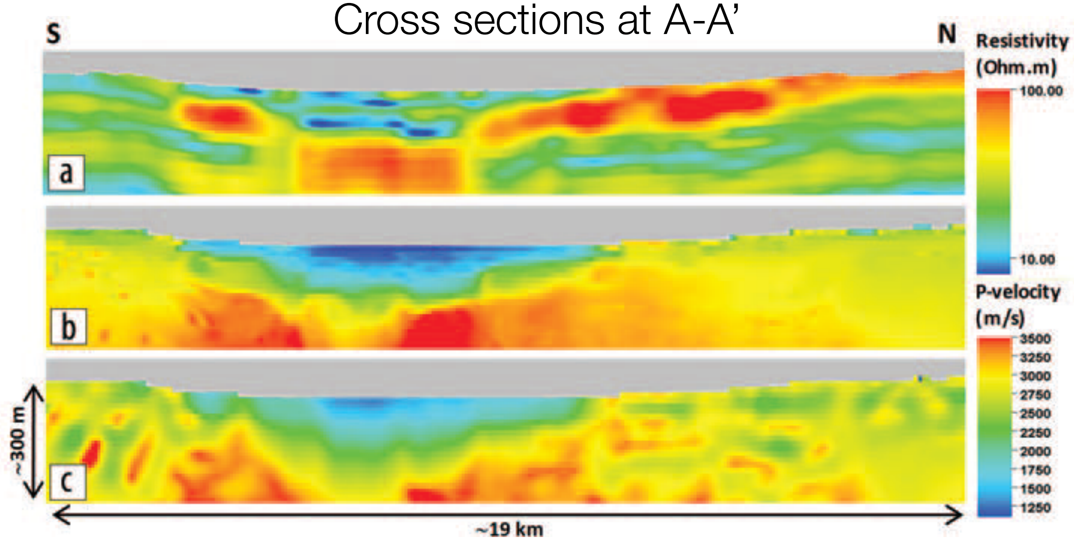


Cross sections at A-A'

Conductivity

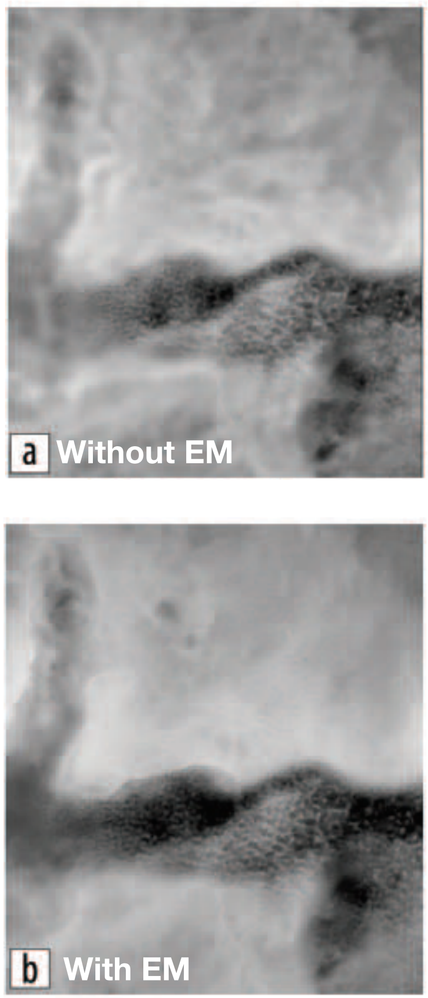
v_p **with EM**

v_p **without EM**

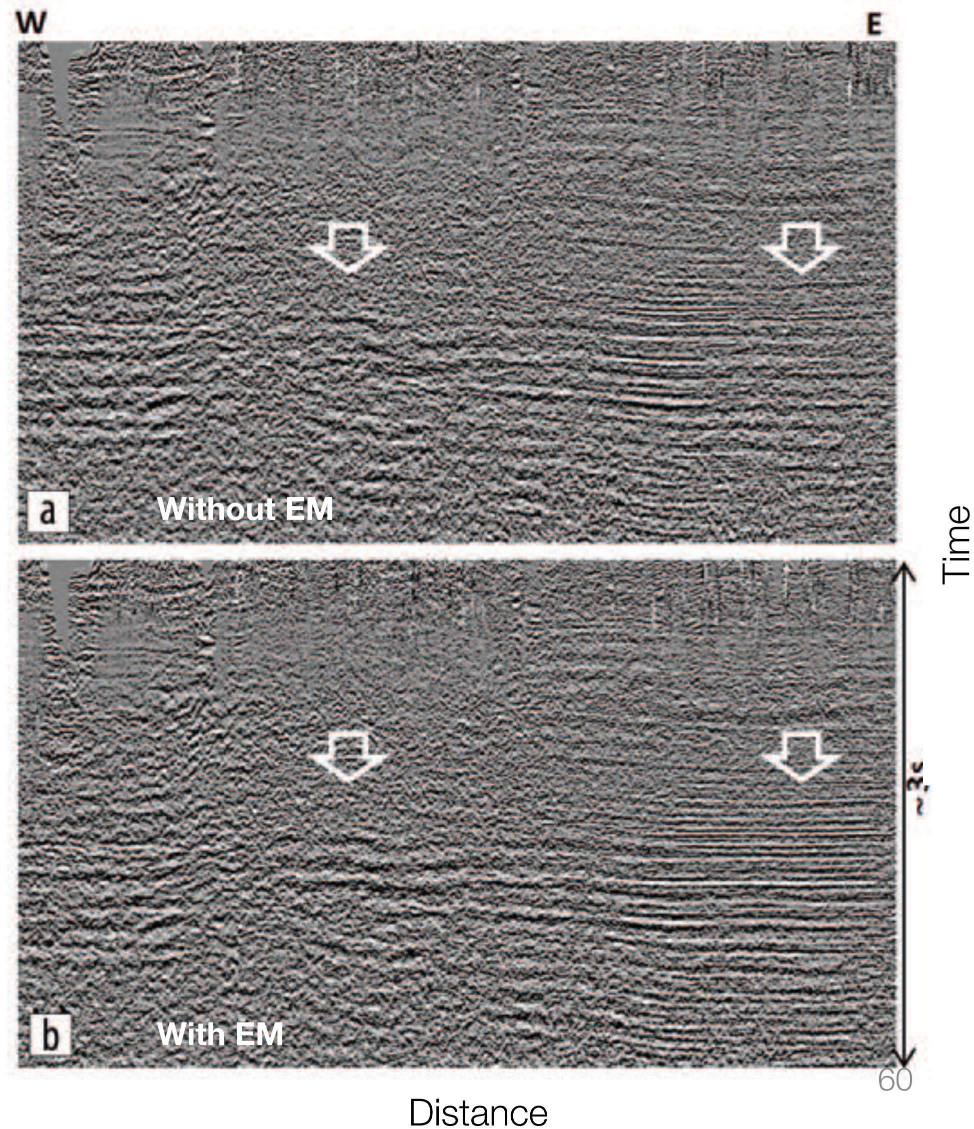


Static correction

Estimated statics on plan map



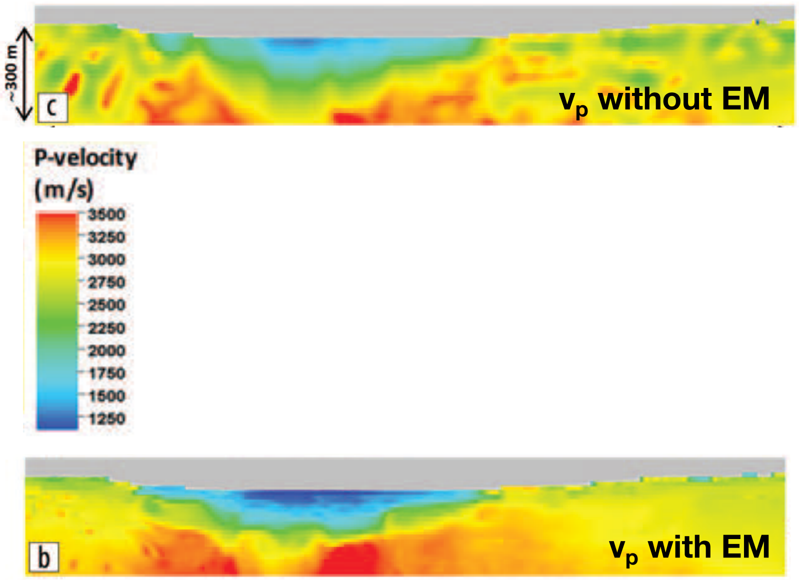
Static corrected sections



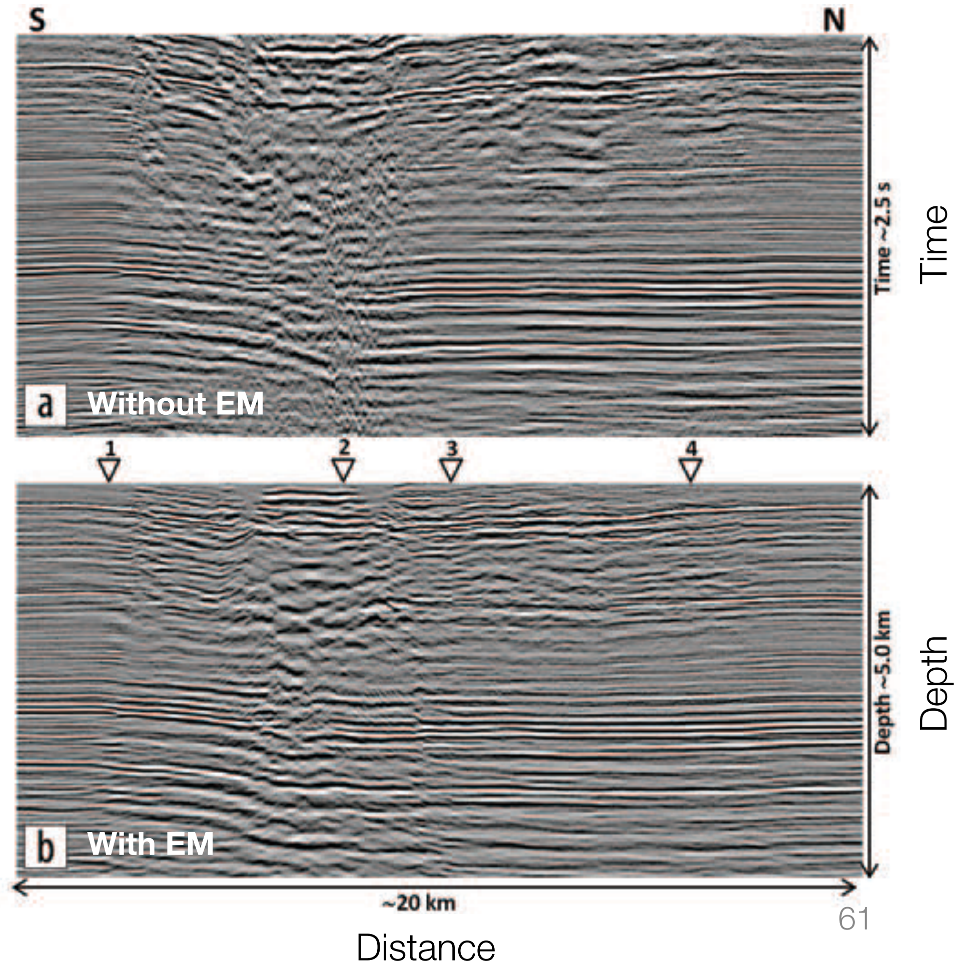
Pre-stack depth migration

- Impact of the improved v_p model to a pre-stack depth migration:

v_p cross sections at A-A'

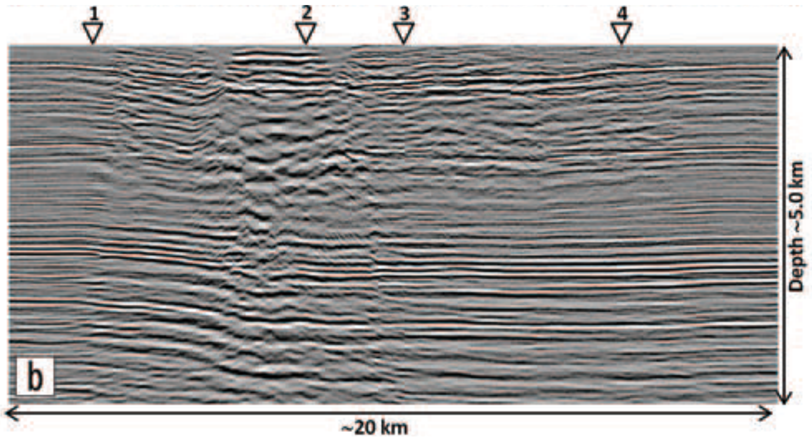


Cross sections at A-A'



Interpretation and Synthesis

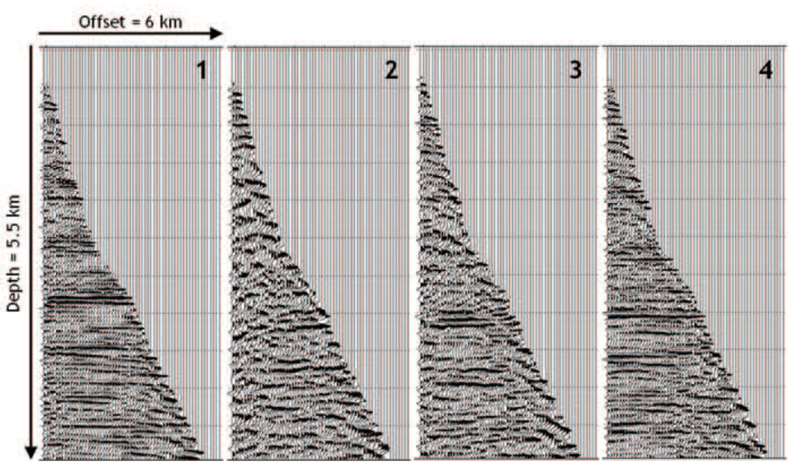
Depth section at A-A'



Distance

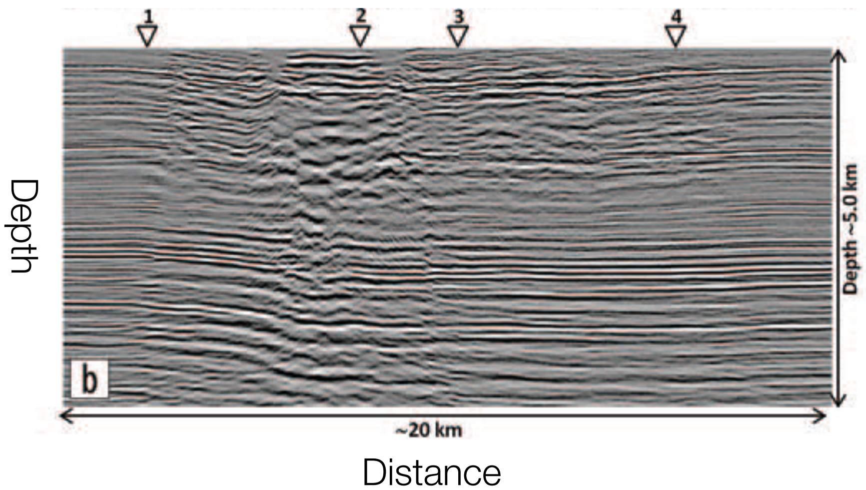
Depth

Common image gathers

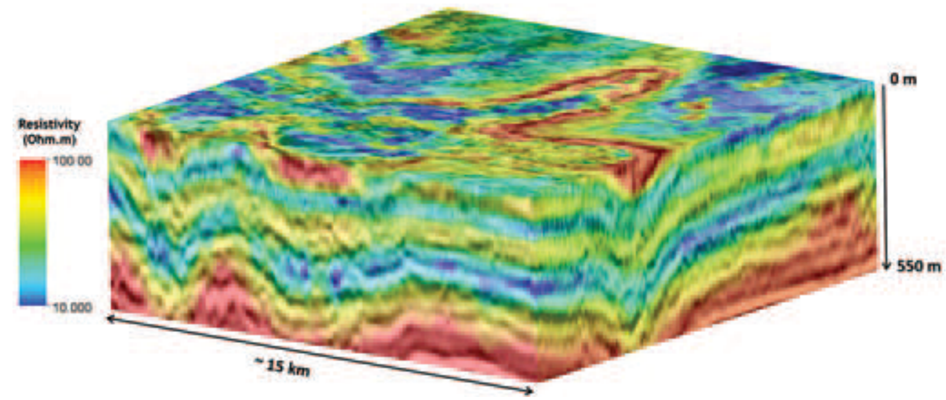


Interpretation and Synthesis

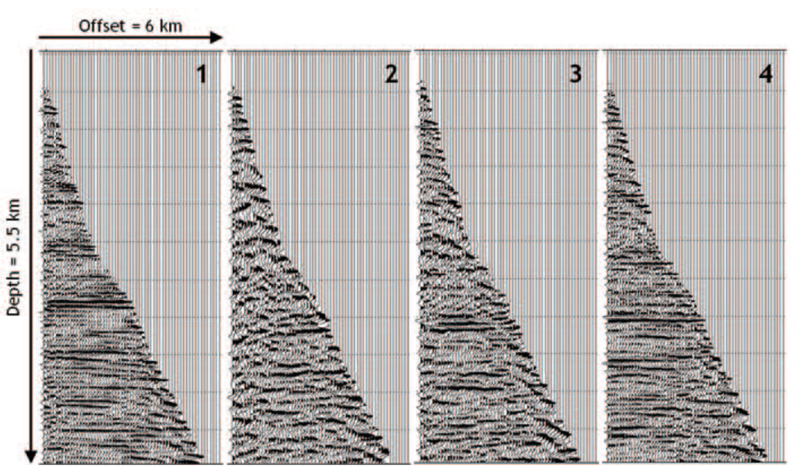
Depth section at A-A'



3D prestack depth migration co-rendered with EM



Common image gathers



- High resolution near surface conductivity from EM improves velocity model
- Helps seismic imaging:
  - Static correction
  - Pre-stack depth migration

Outline

Setup

- Basic experiment
- Transmitters, Receivers

Time Domain EM

- Vertical Magnetic Dipole
- Propagation with Time
- Case History

Frequency Domain EM

- Vertical Magnetic Dipole
- Effects of Frequency
- Case History – Groundwater

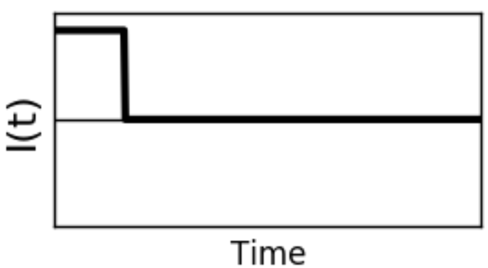
EM with Inductive Sources

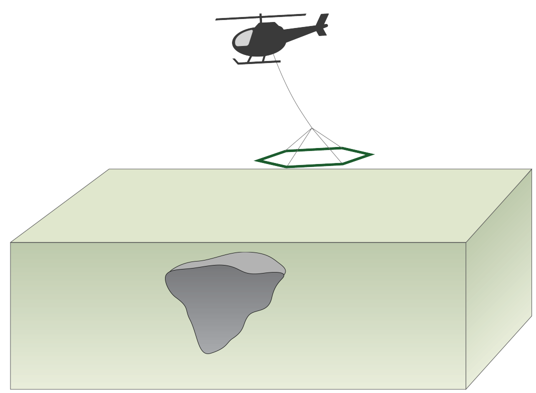
- Induction principles are the same for
  - TDEM: Time domain EM
  - FDEM: Frequency domain EM

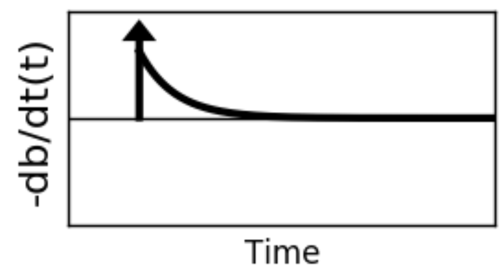
Transmitter current

Receiver

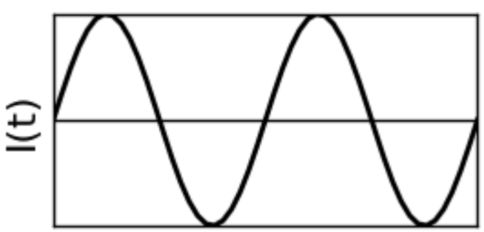
TDEM

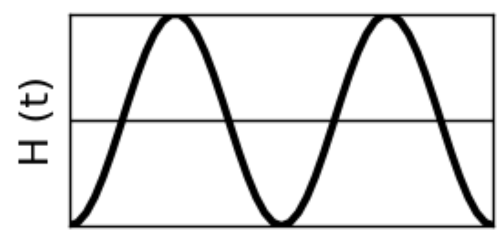




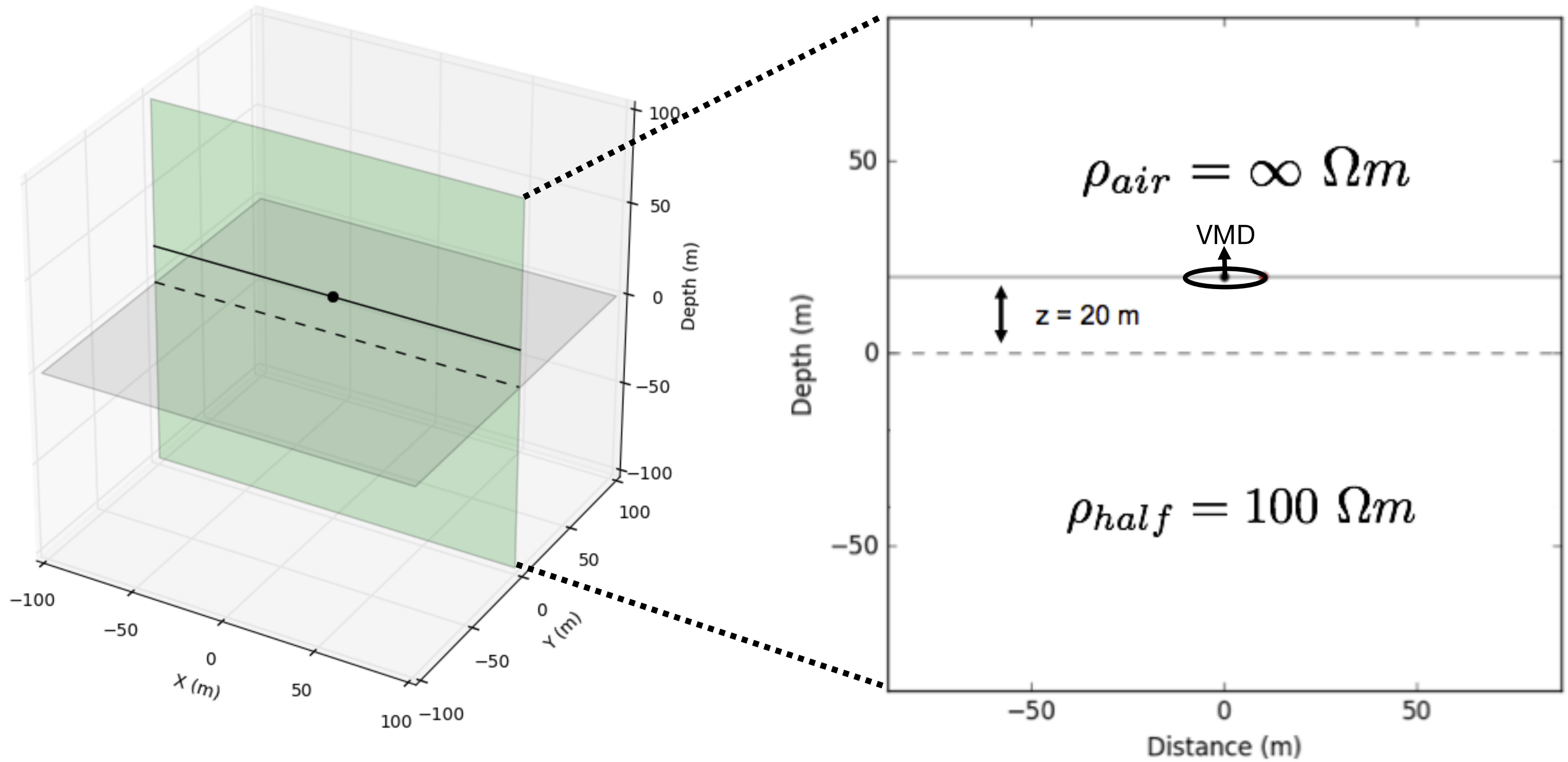


FDEM



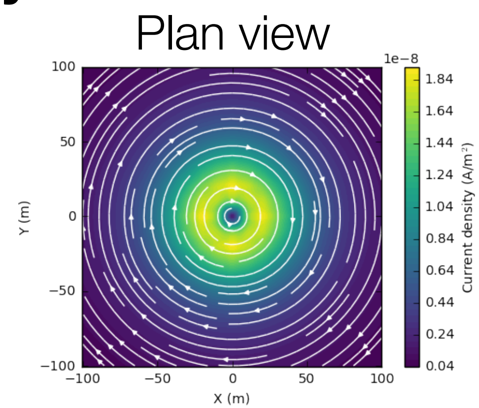


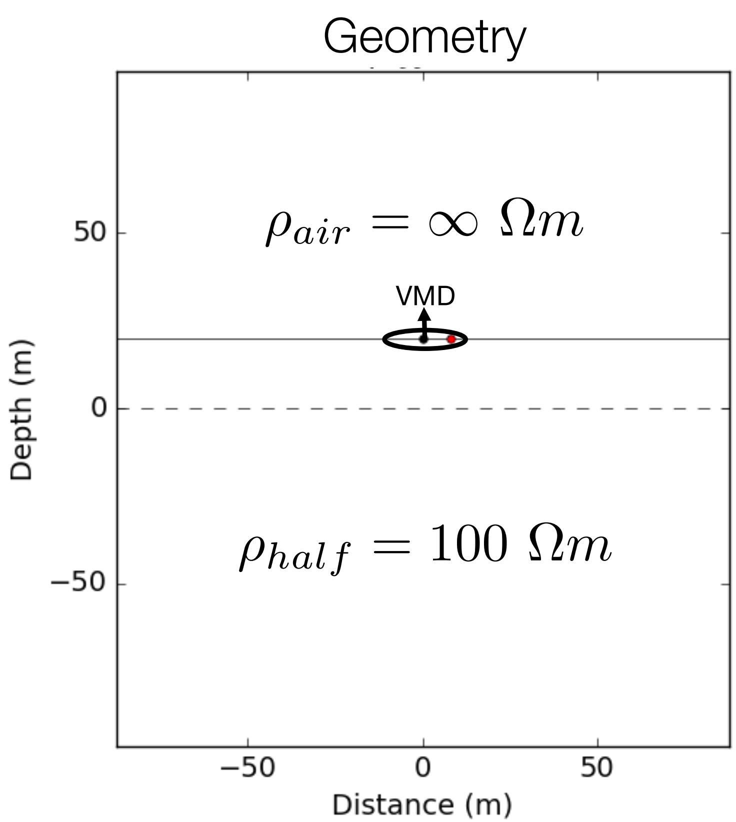
Vertical Magnetic Dipole over a halfspace (FDEM)

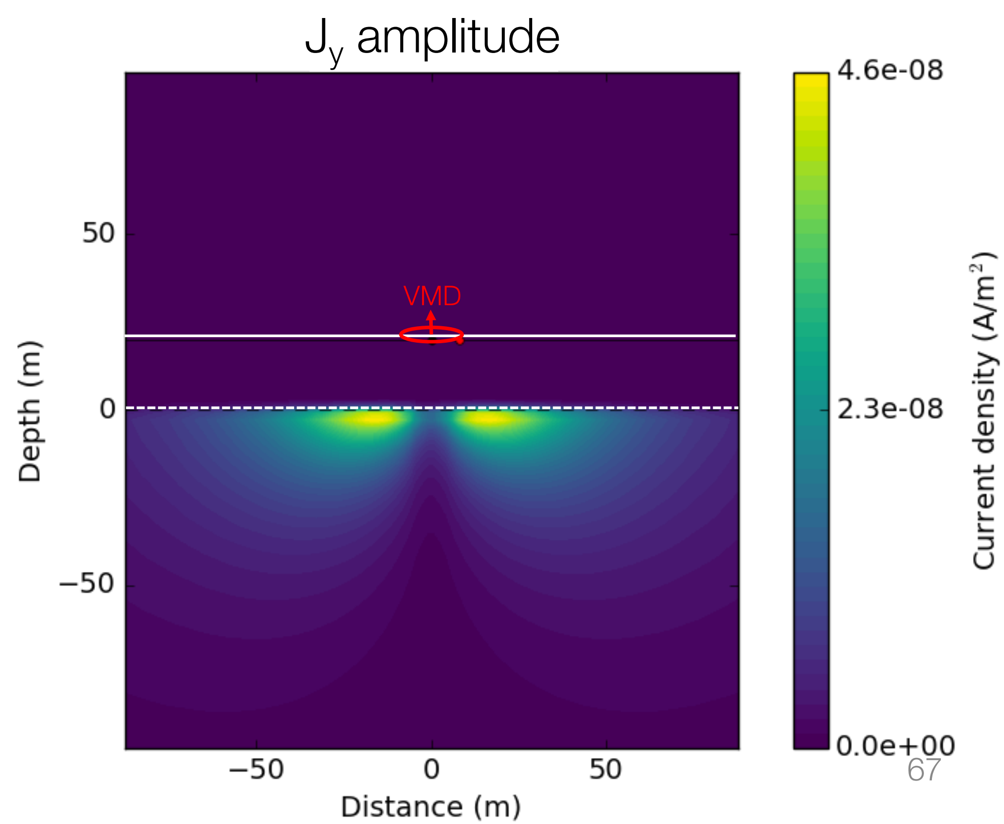


Current Density

- Frequency = 10 kHz
- Currents in the earth flow in planes parallel to the Tx

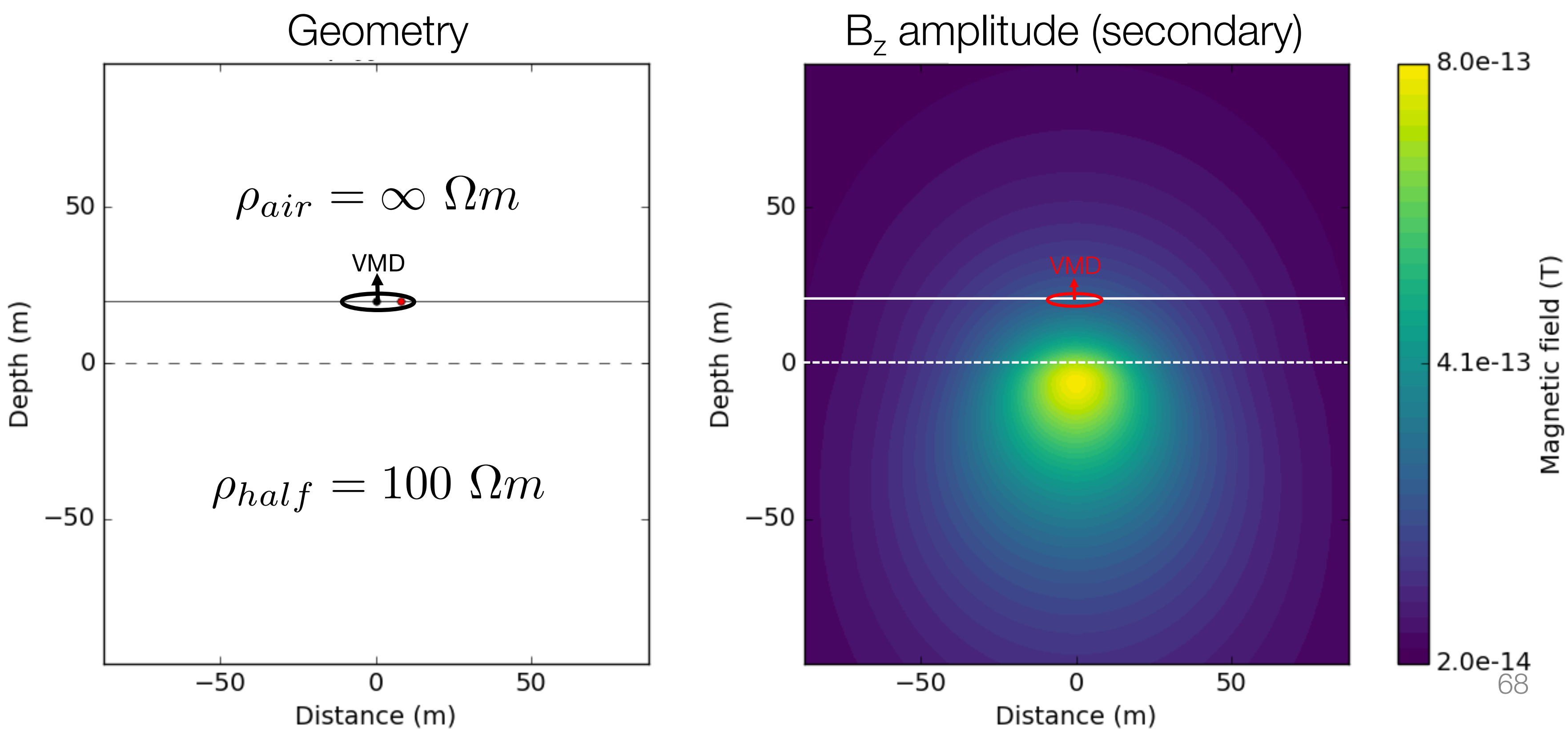






Secondary Magnetic Flux Density

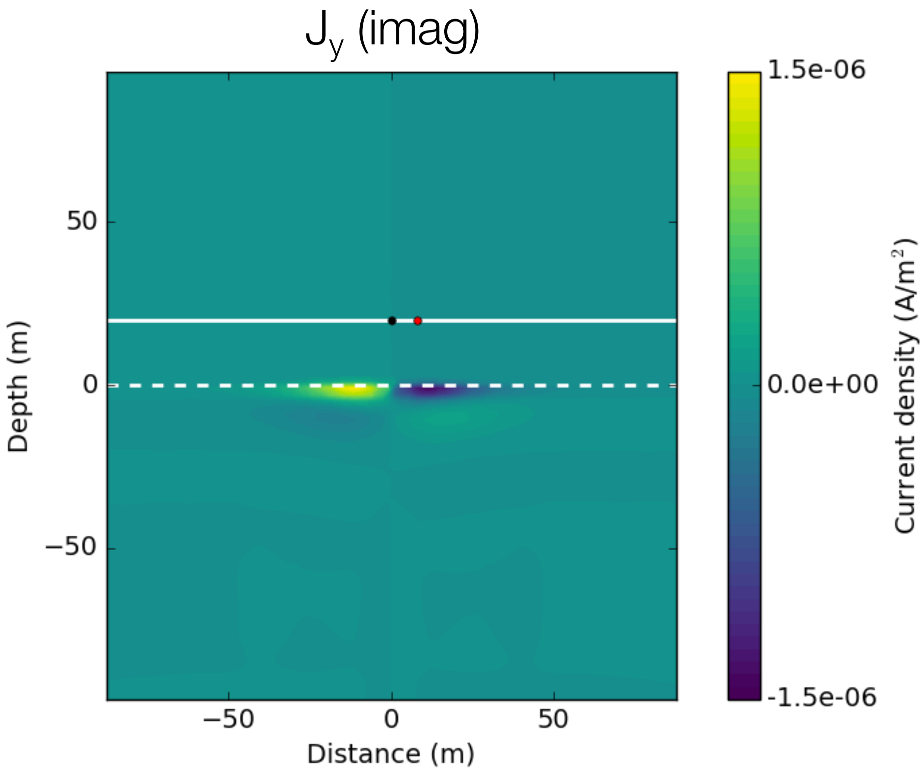
- Frequency = 10 kHz

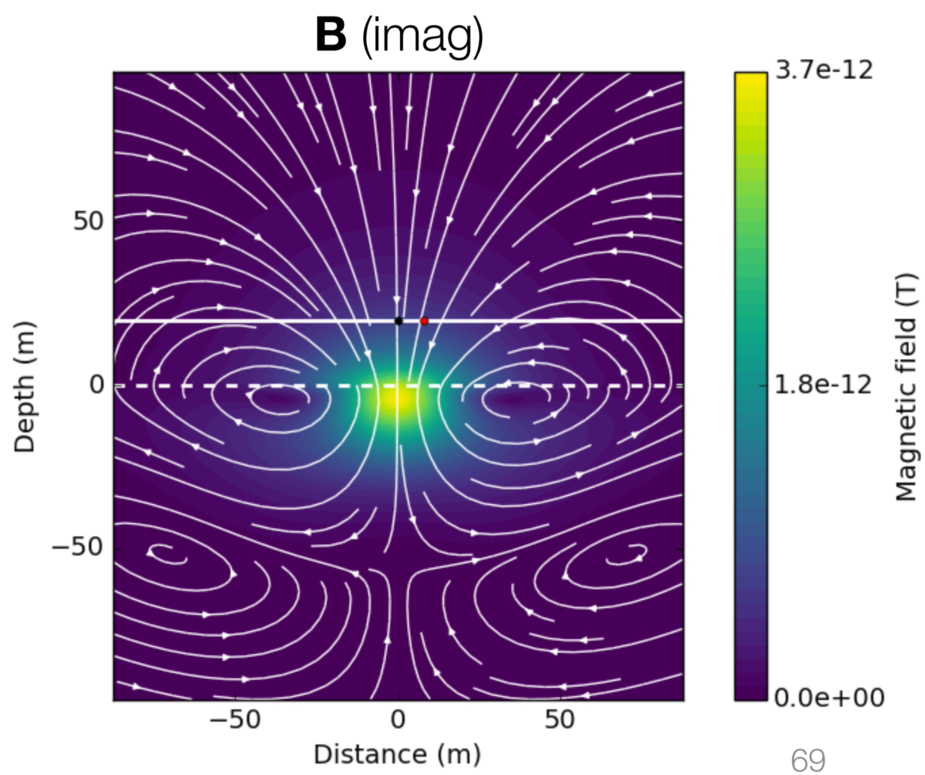


Effects of Frequency

- Frequency at 100 kHz
- Skin depth = 16 m
- Currents are concentrated at surface

$$\delta = 503\sqrt{\frac{\rho}{f}}$$

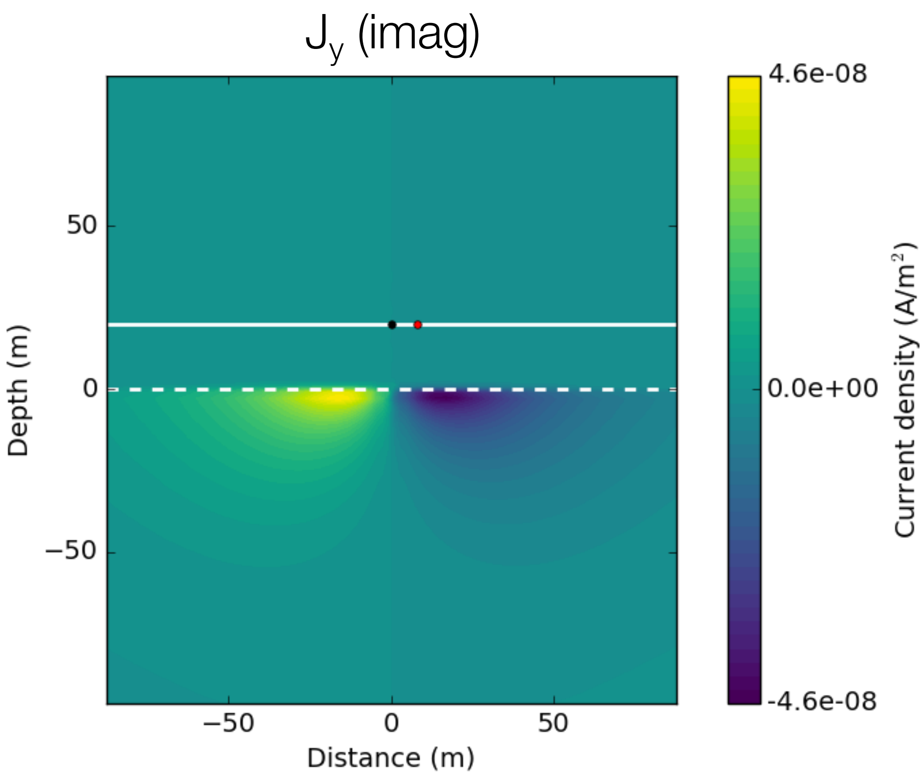


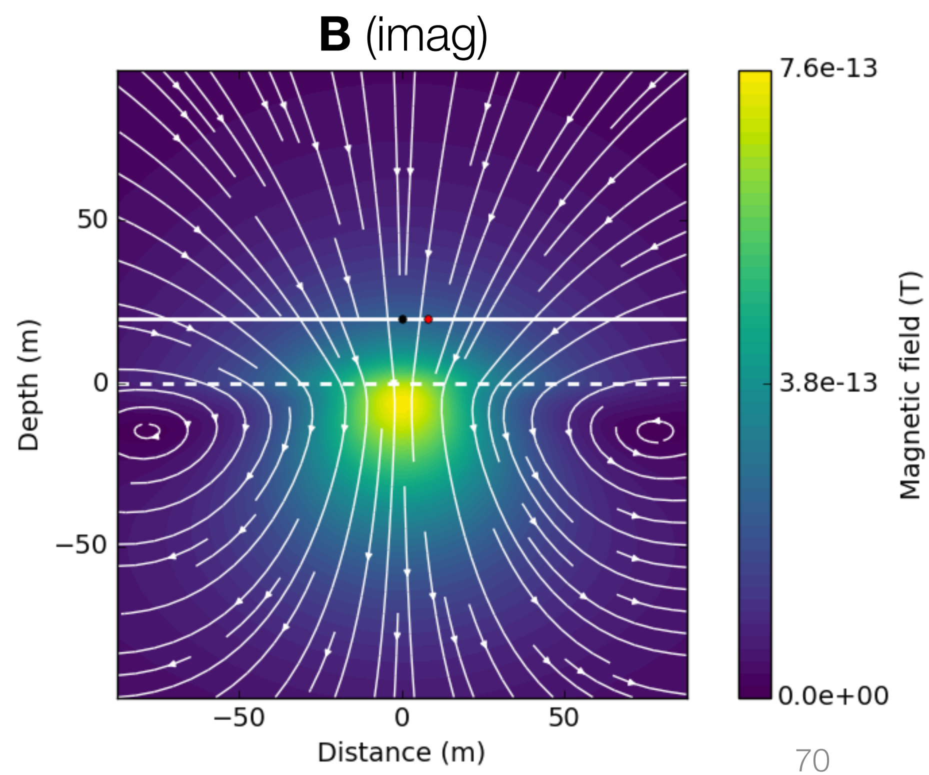


Effects of Frequency

- Frequency at 10 kHz
- Skin depth = 50 m
- Currents diffusing downward and outward

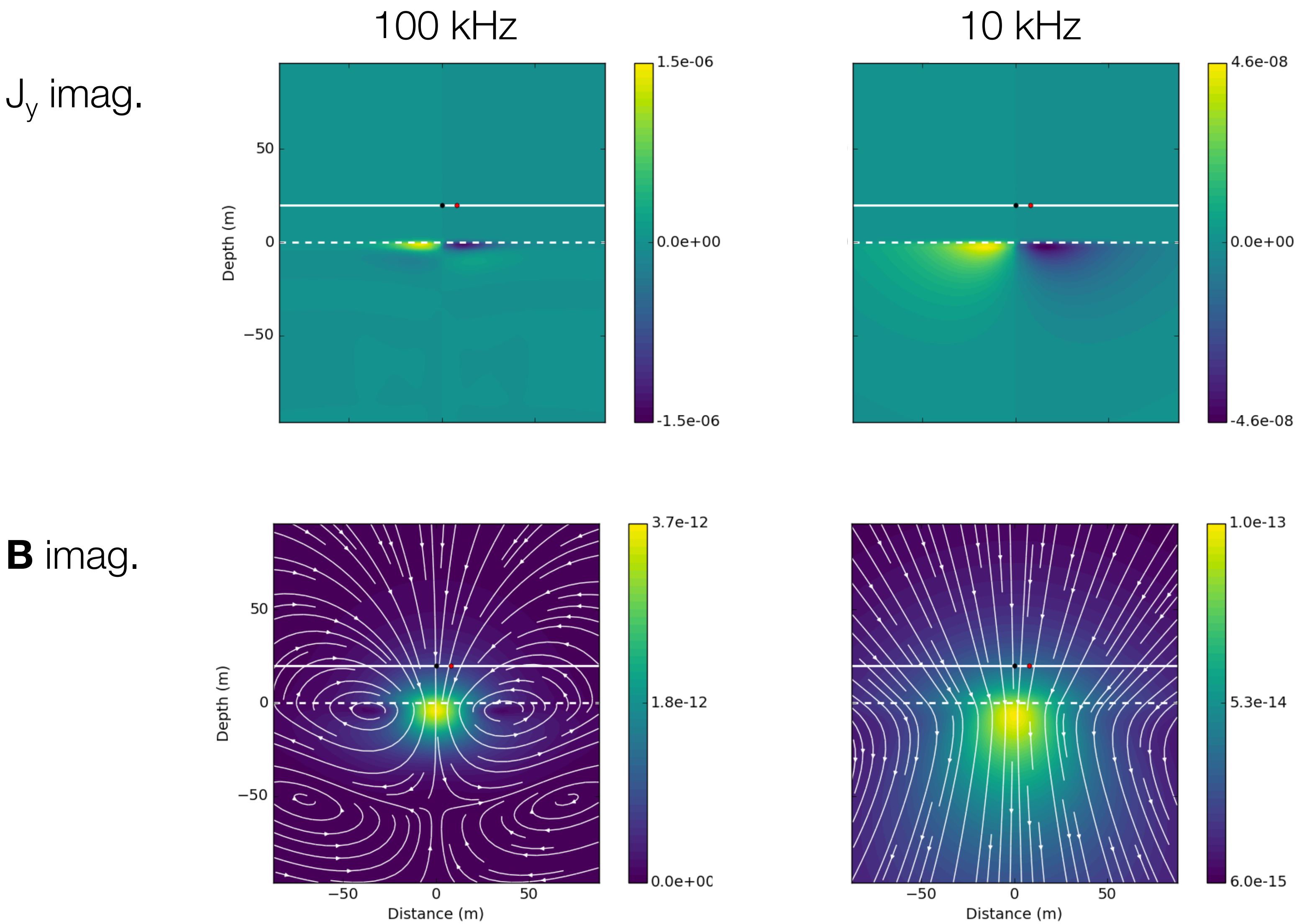
$$\delta = 503\sqrt{\frac{\rho}{f}}$$





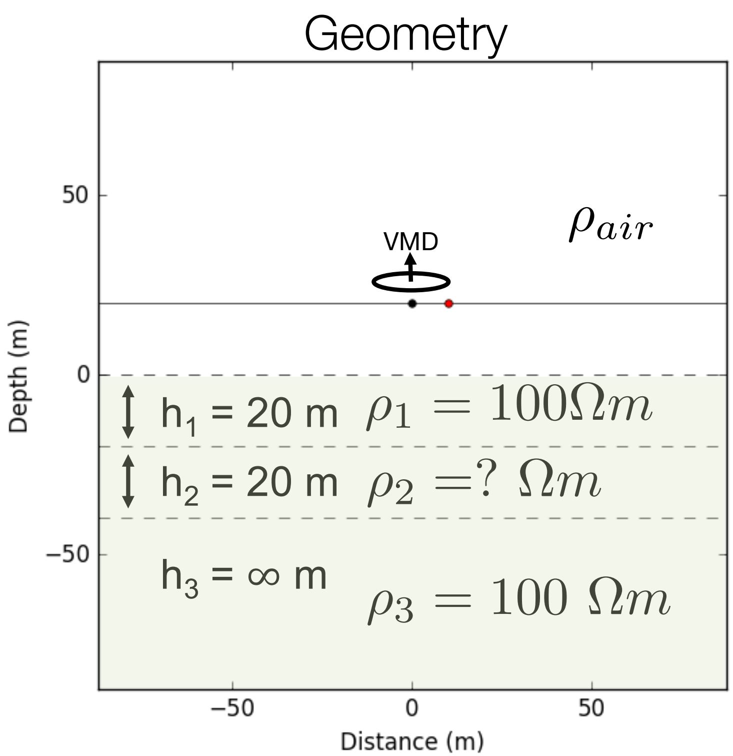
Summary: Effects of Frequency

$$\delta = 503\sqrt{\frac{\rho}{f}}$$



Layered earth

- 3 layers + air,
- ρ_2 varies



- Four different cases:
  - Halfspace

    $\rho_2 = 100\ \Omega\mathrm{m}$
  - Resistive

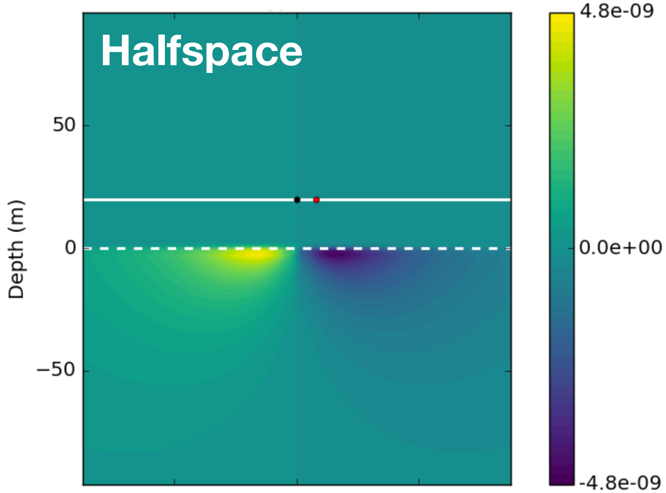
    $\rho_2 = 1000\ \Omega\mathrm{m}$
  - Conductive

    $\rho_2 = 10\ \Omega\mathrm{m}$
  - Very conductive

    $\rho_2 = 1\ \Omega\mathrm{m}$
- Fields
  - J_y imag
  - Secondary **B** imag

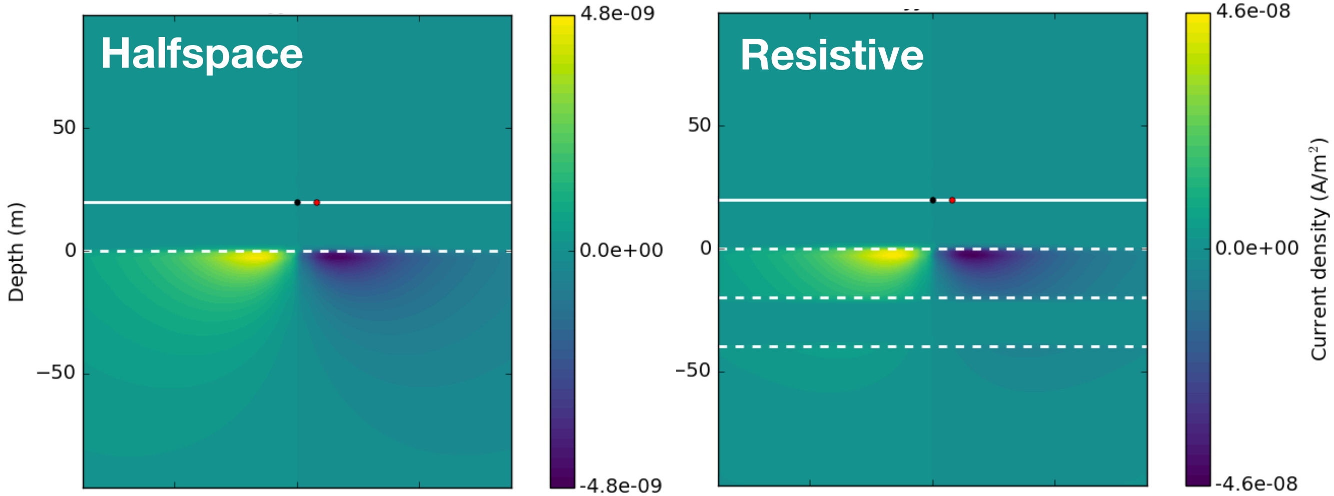
Current density (J_y imag)

$\rho_2 = 100\ \Omega\mathrm{m}$

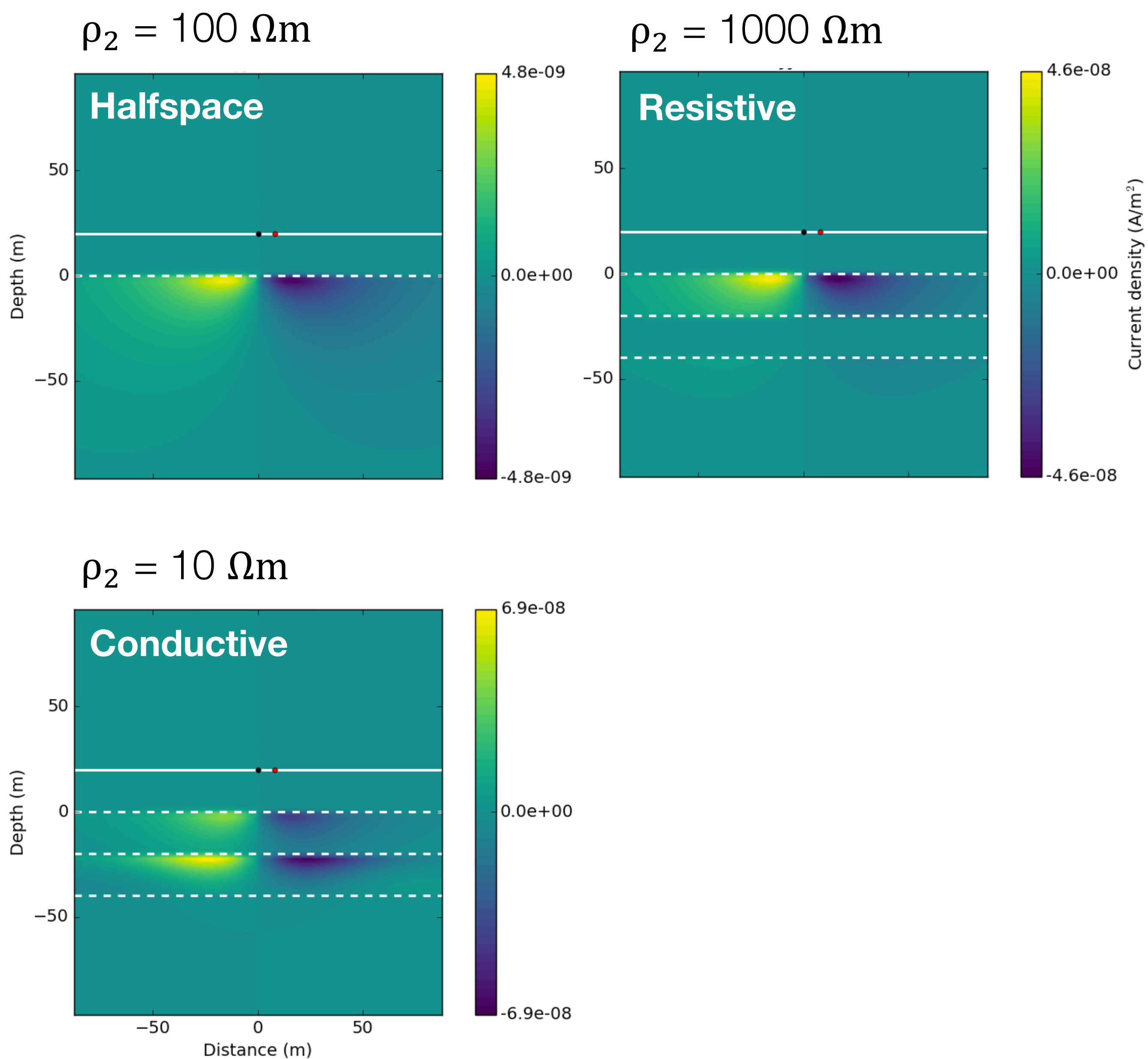


Current density (J_y imag)

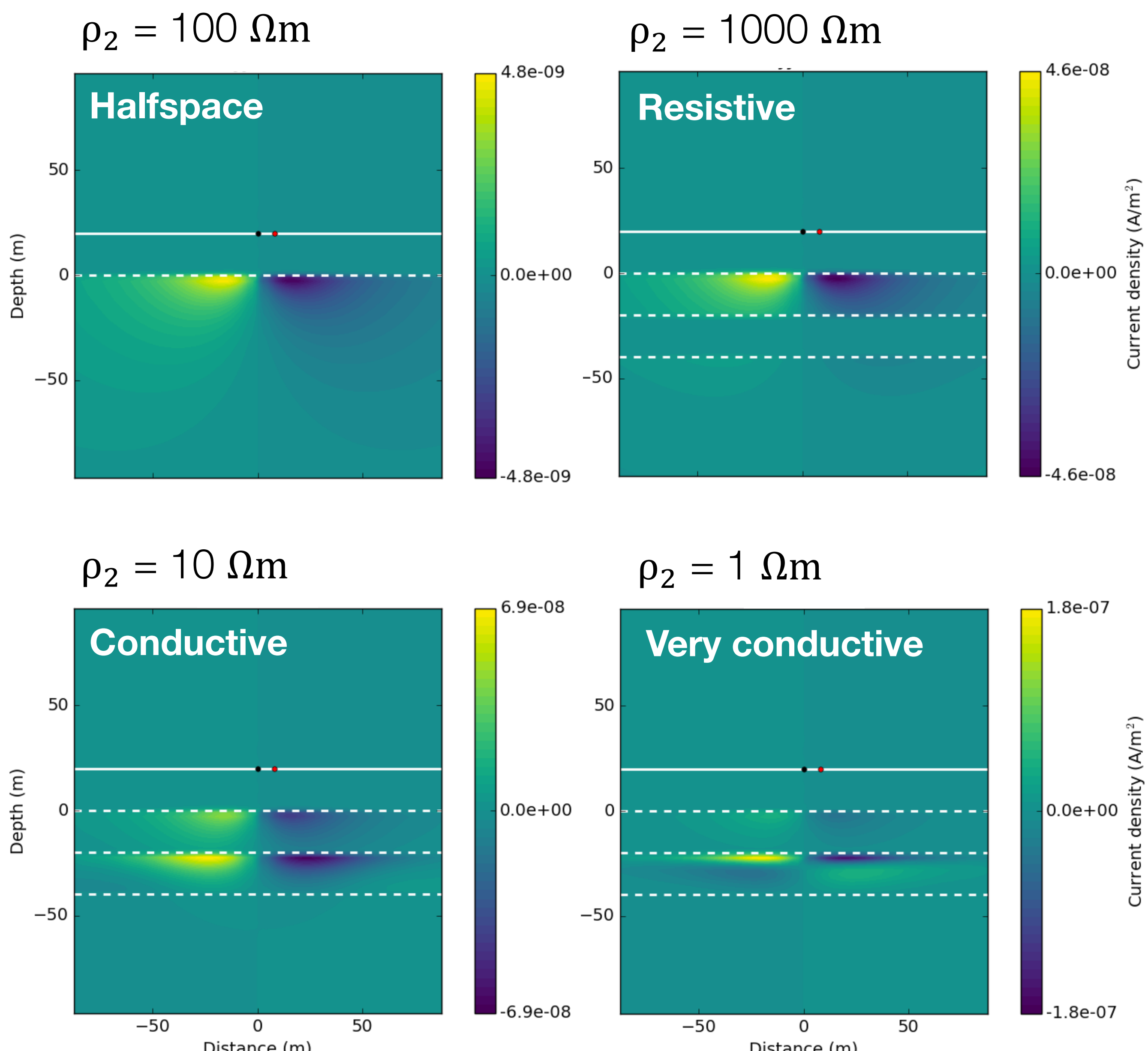
$\rho_2 = 100\ \Omega m$ $\rho_2 = 1000\ \Omega m$



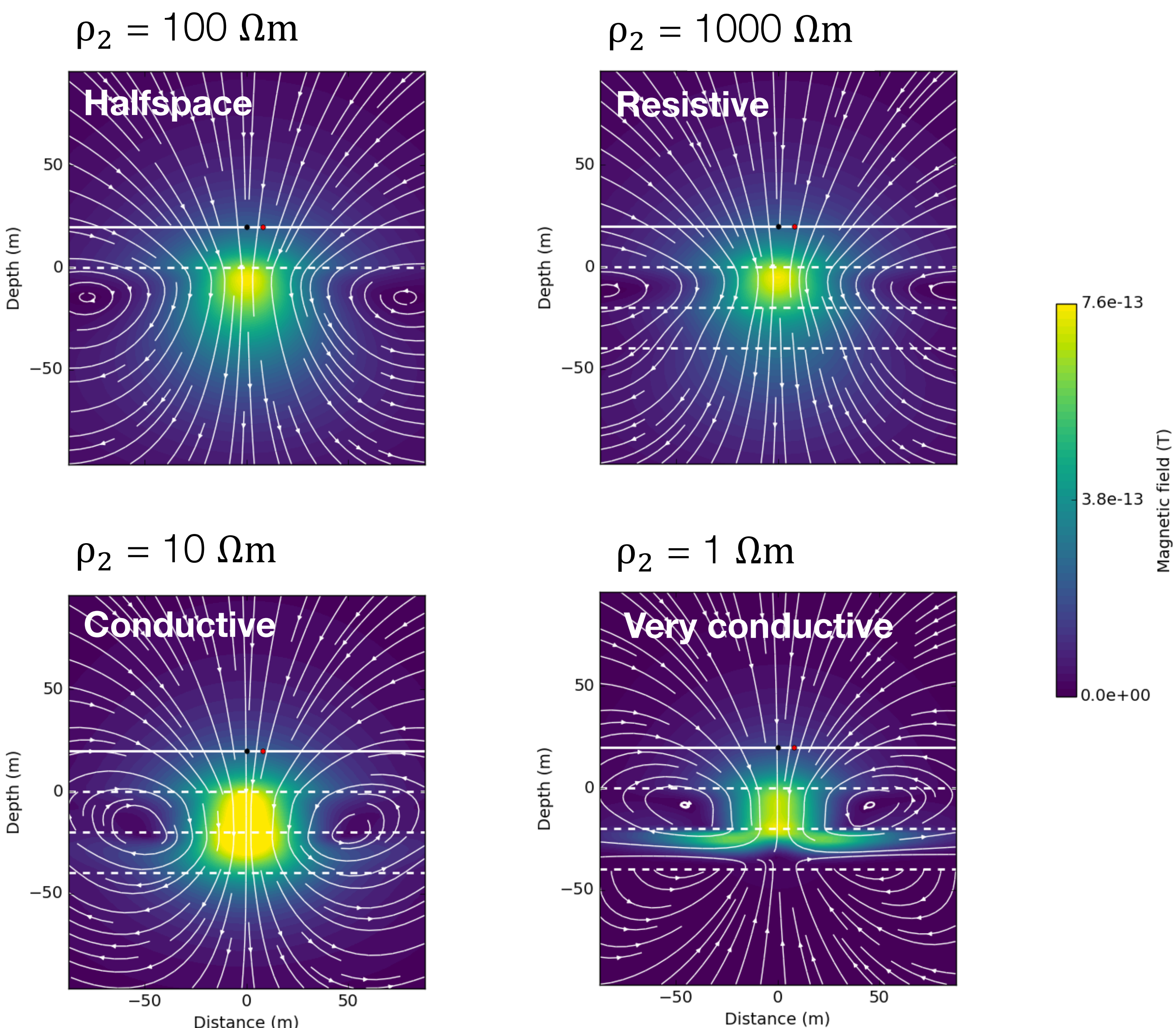
Current density (J_y imag)



Current density (J_y imag)

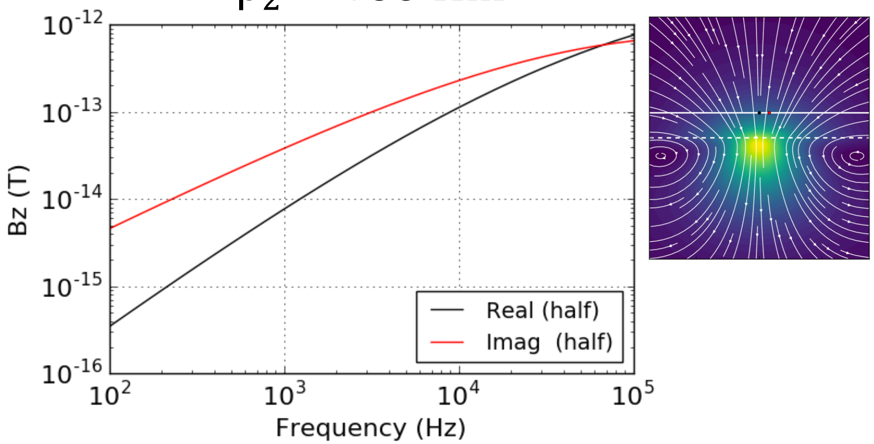


Magnetic flux density (**B** imag)

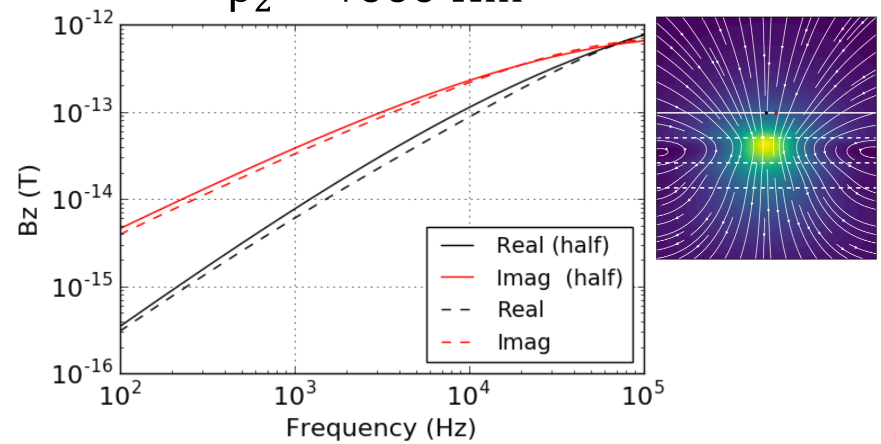


B_z sounding curves

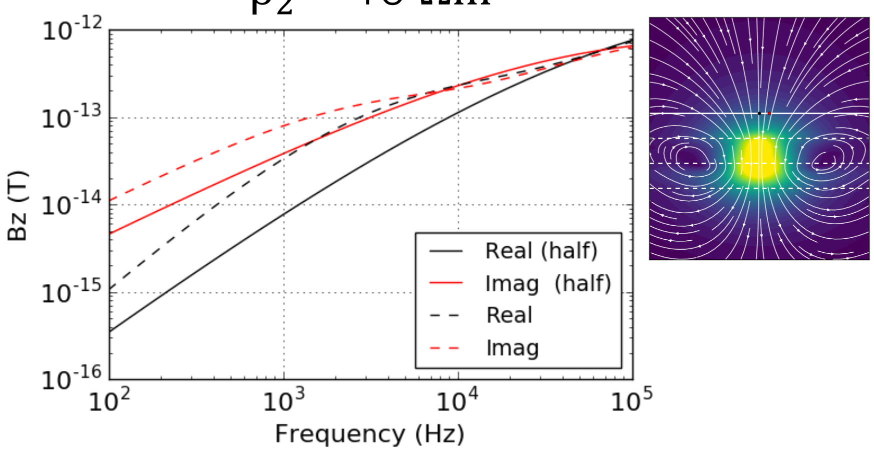
ρ_2 = 100 Ωm



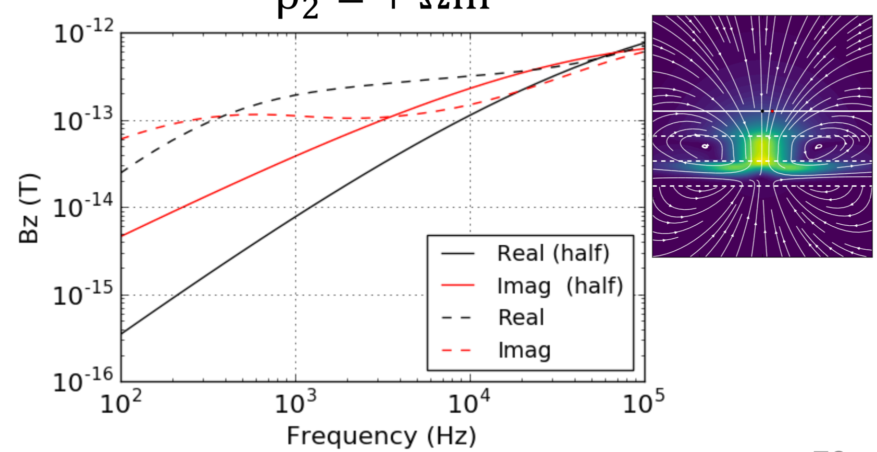
ρ_2 = 1000 Ωm



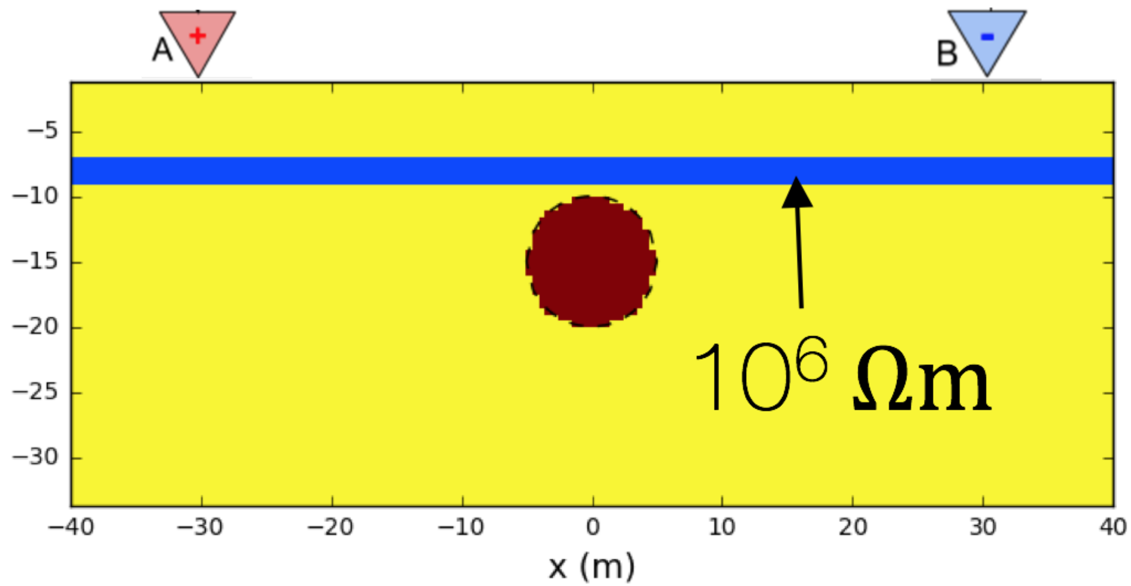
ρ_2 = 10 Ωm



ρ_2 = 1 Ωm

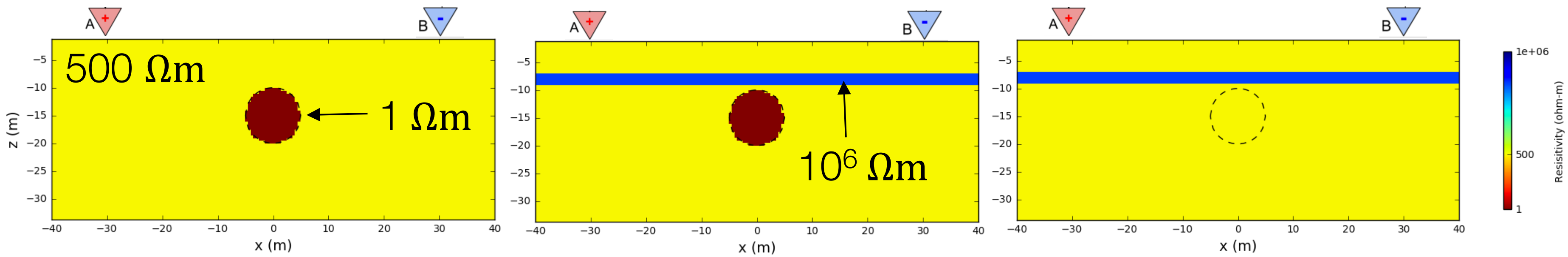


Back to the “shielding” problem



Shielding: DC with resistive layer

Resistivity models (thin **resistive** layer)

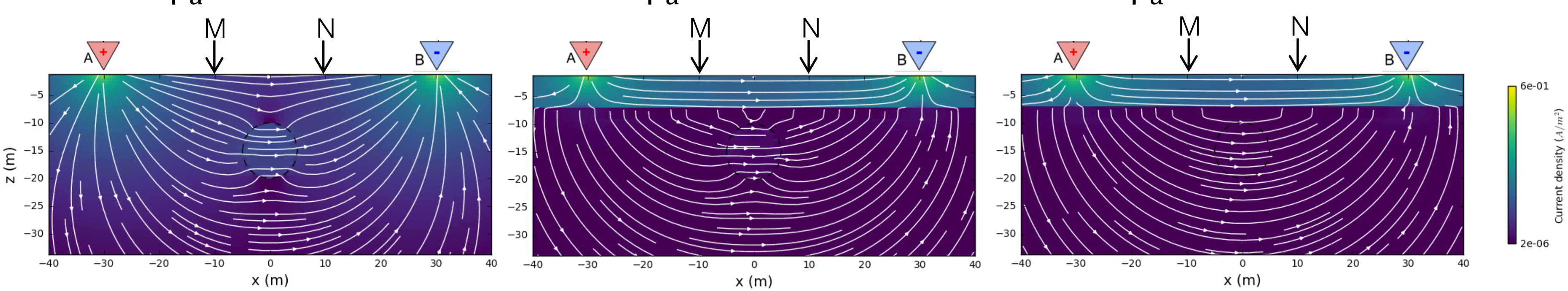


Currents and measured data at MN

ρ_a = 430 Ωm

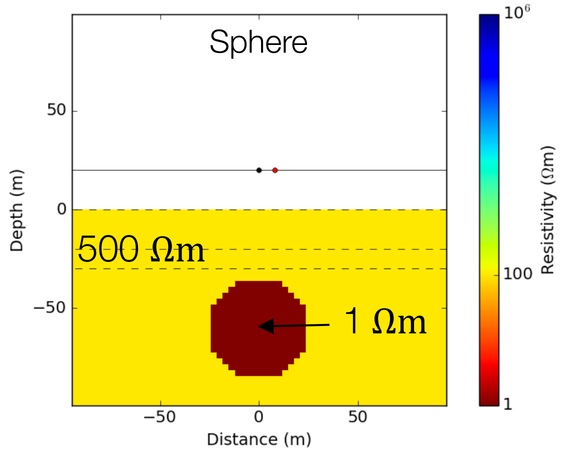
ρ_a = 1652 Ωm

ρ_a = 1654 Ωm

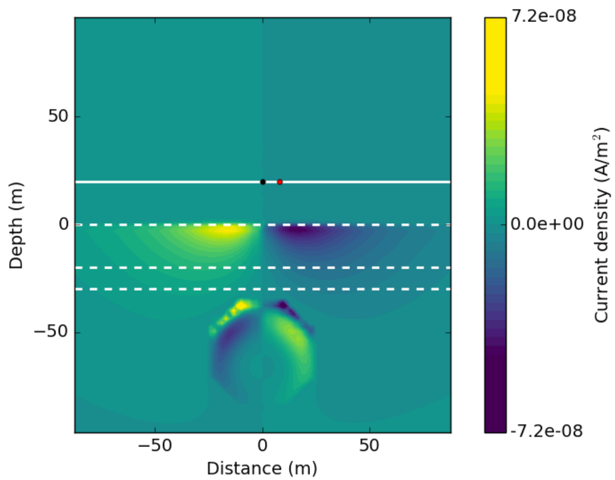


Shielding: EM with resistive layer

Resistivity models (thin **resistive** layer)

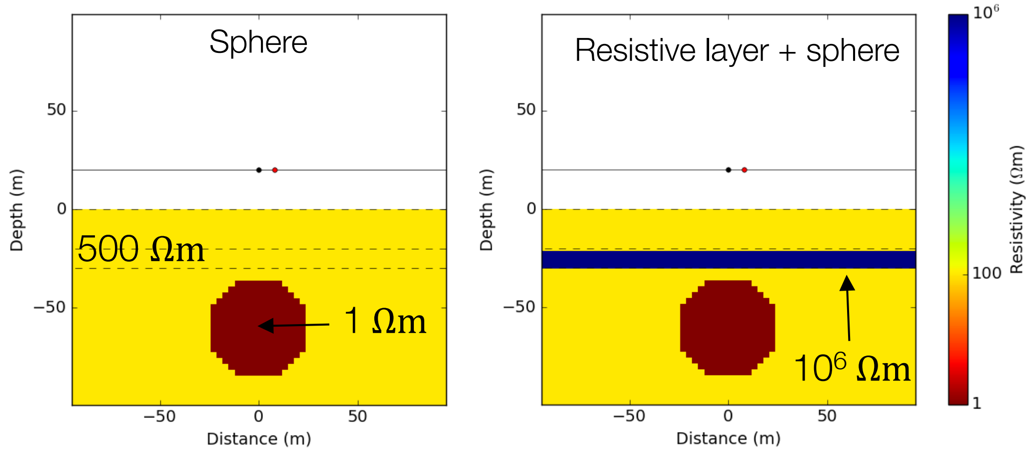


Currents (J_y imag)

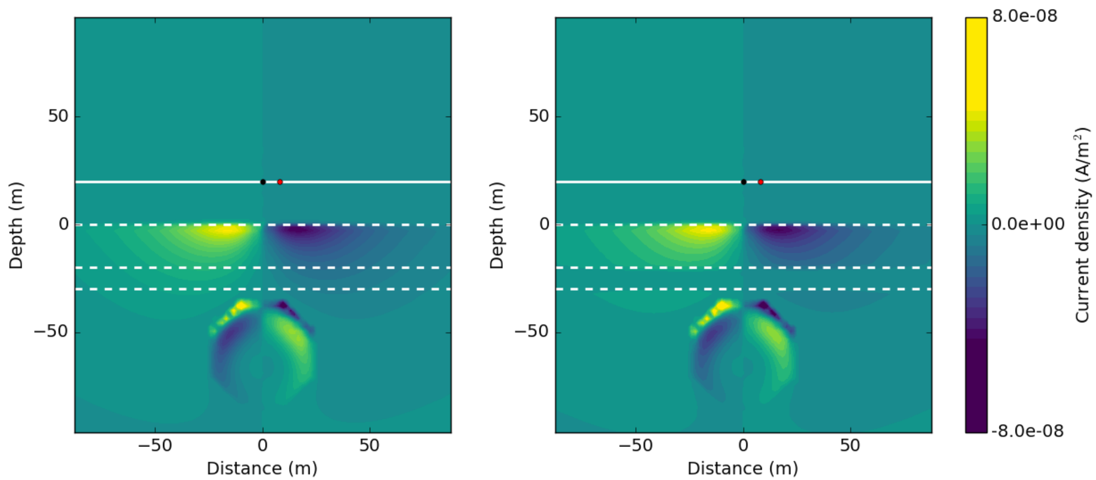


Shielding: EM with resistive layer

Resistivity models (thin **resistive** layer)

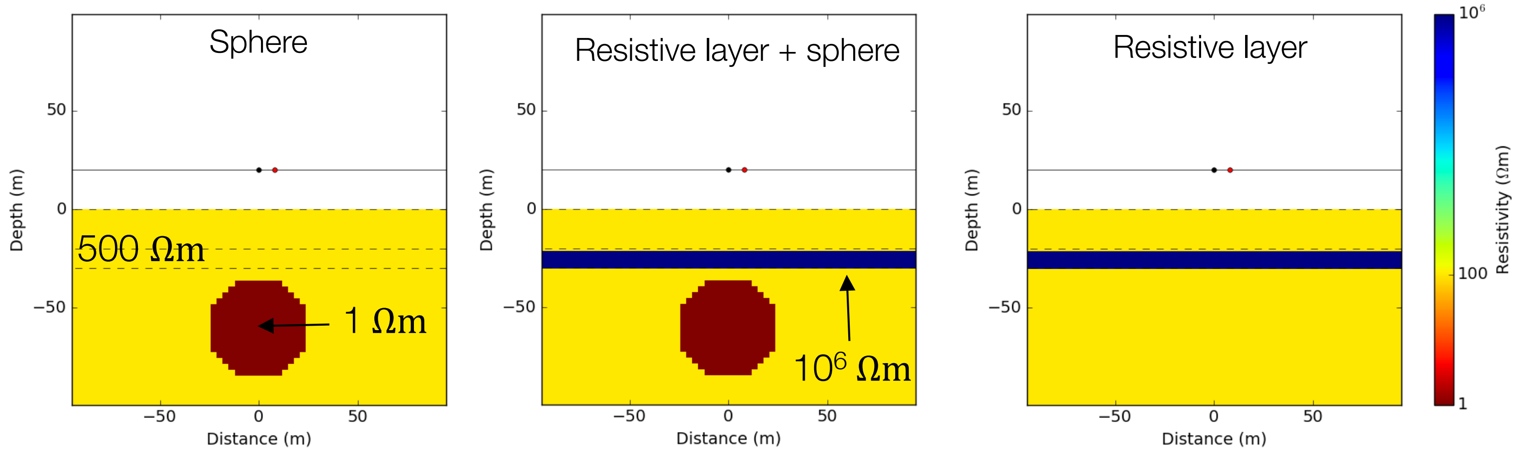


Currents (J_y imag)

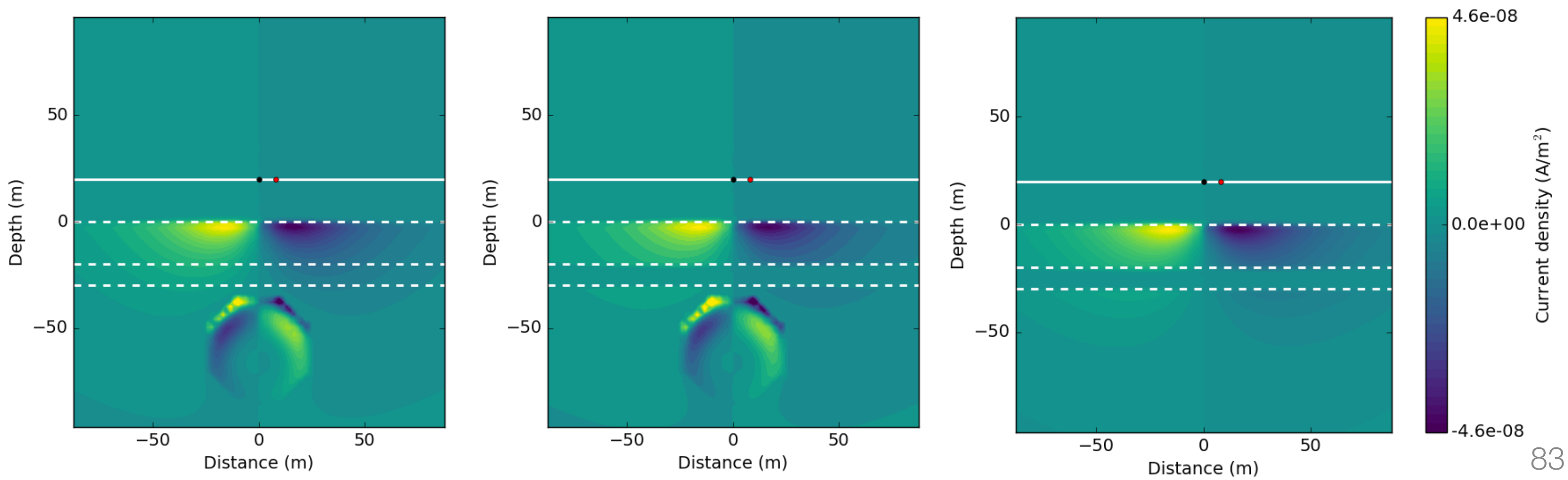


Shielding: EM with resistive layer

Resistivity models (thin **resistive** layer)

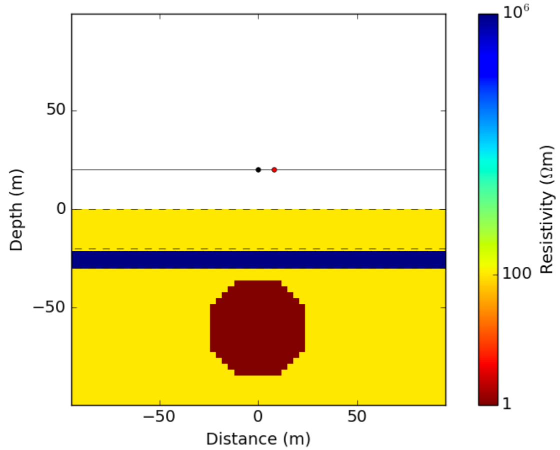


Currents (J_y imag)

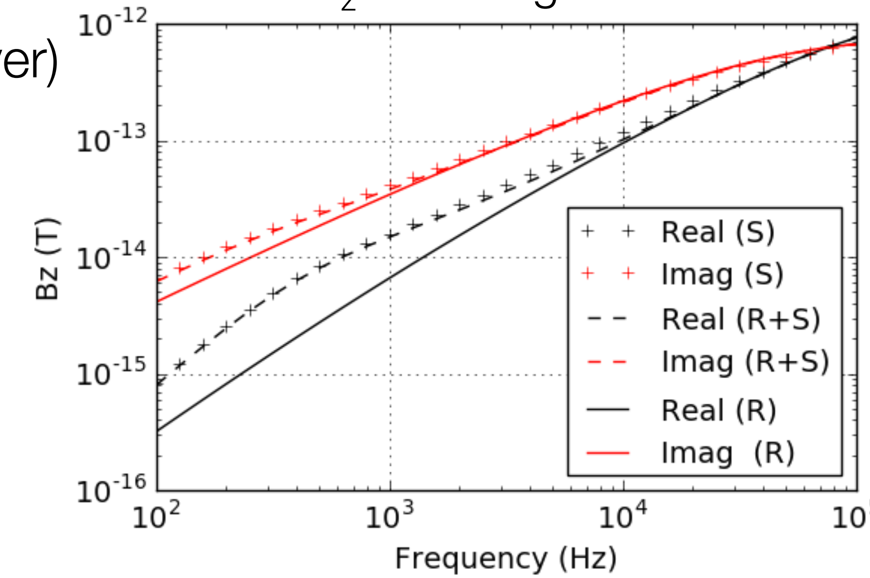


Shielding: EM with resistive layer

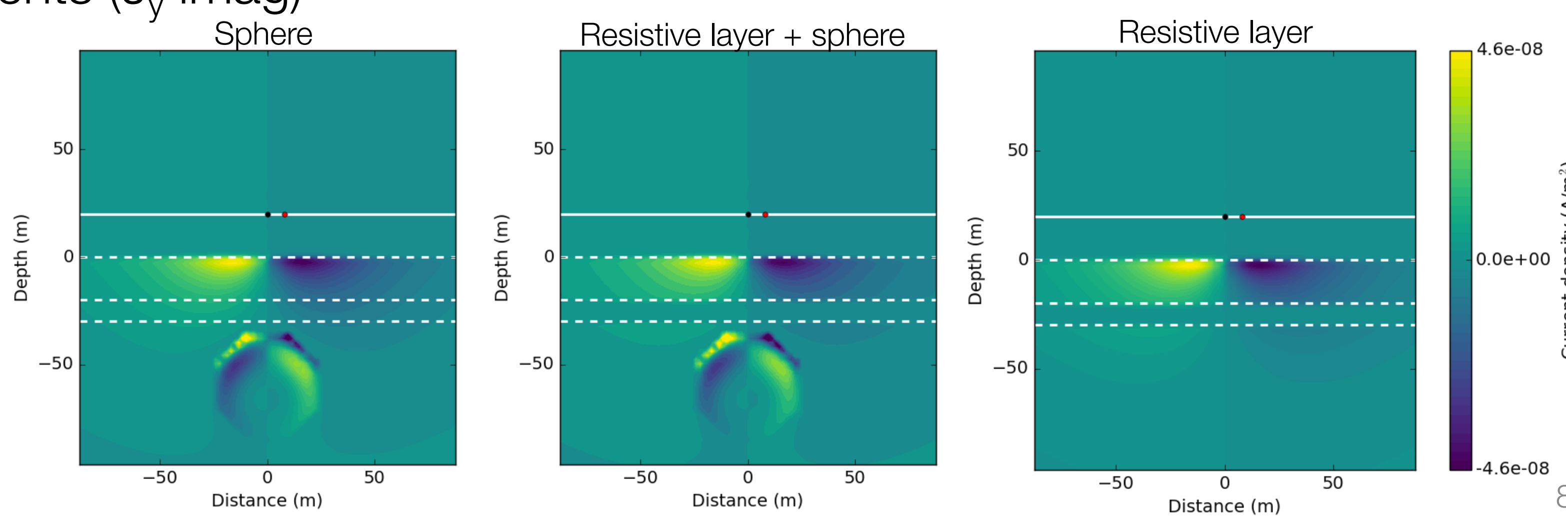
Resistivity models (thin **resistive** layer)



B_z sounding curves

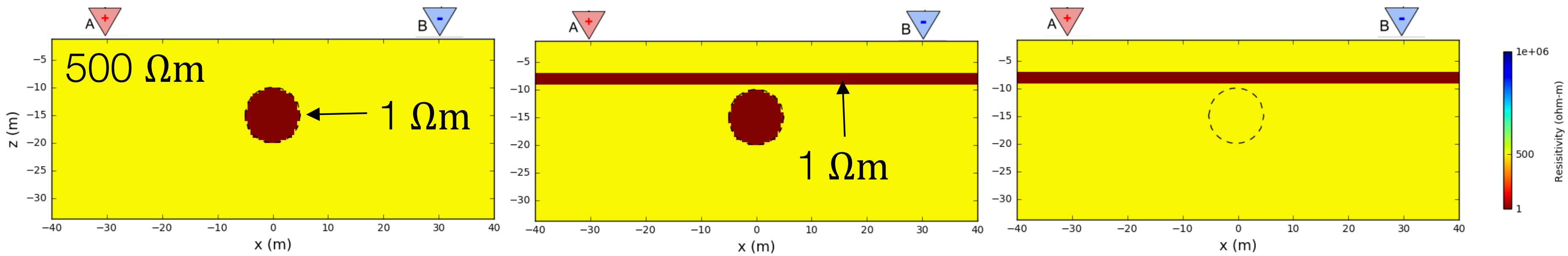


Currents (J_y imag)

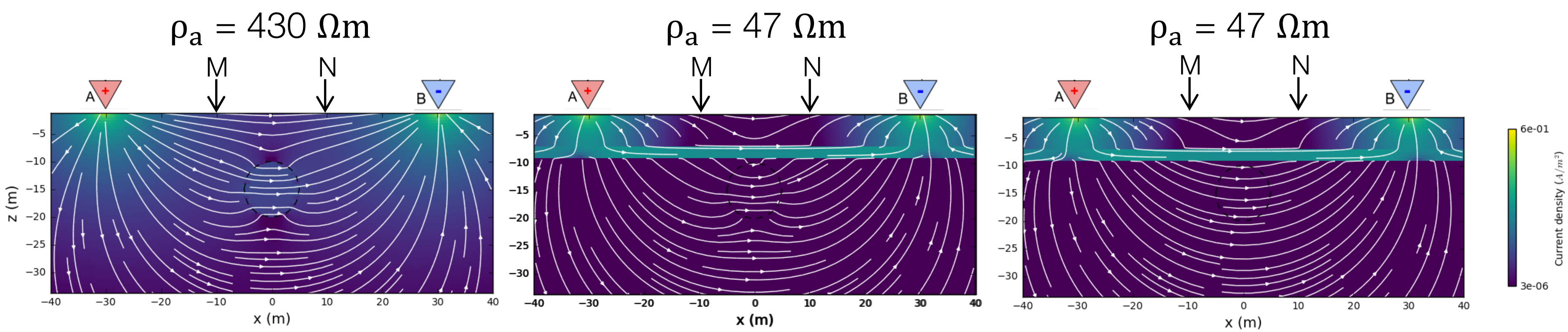


Shielding: DC with conductive layer

Resistivity models (thin **conductive** layer)

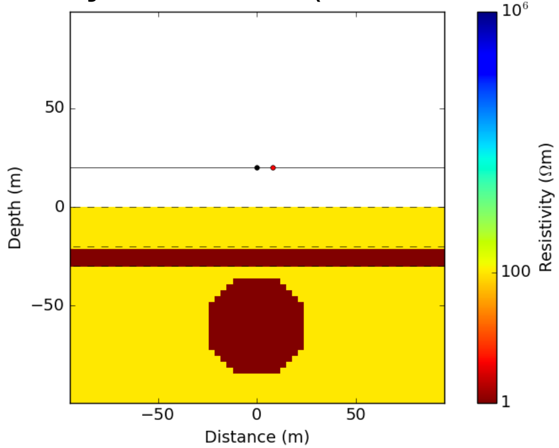


Currents and measured data at MN

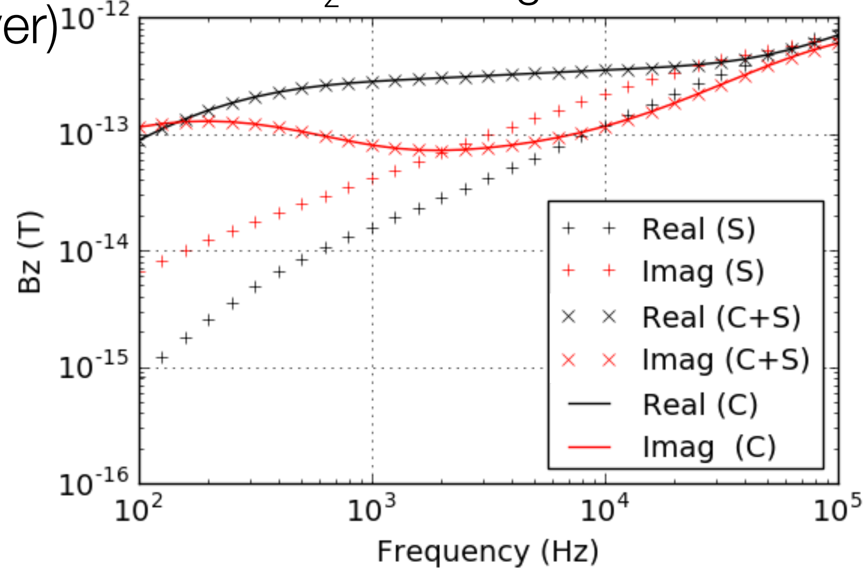


Shielding: EM with conductive layer

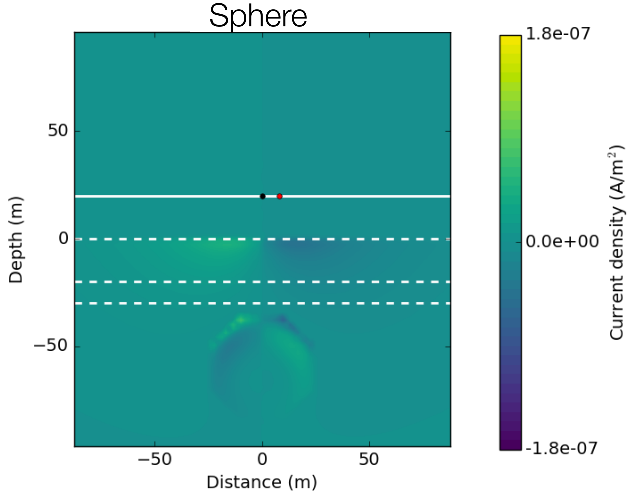
Resistivity models (thin **conductive** layer)



B_z sounding curves

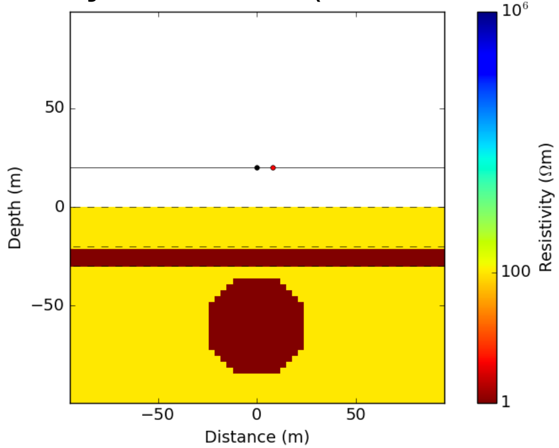


Currents (J_y imag)

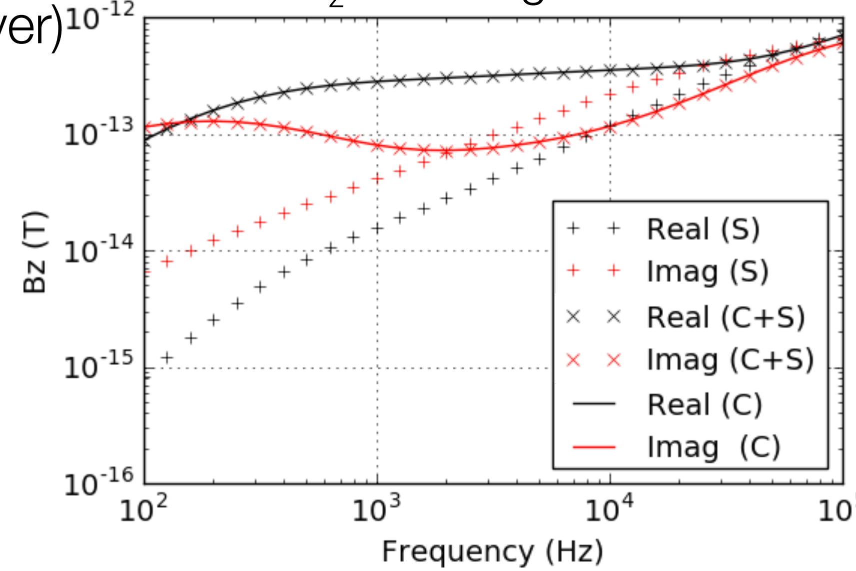


Shielding: EM with conductive layer

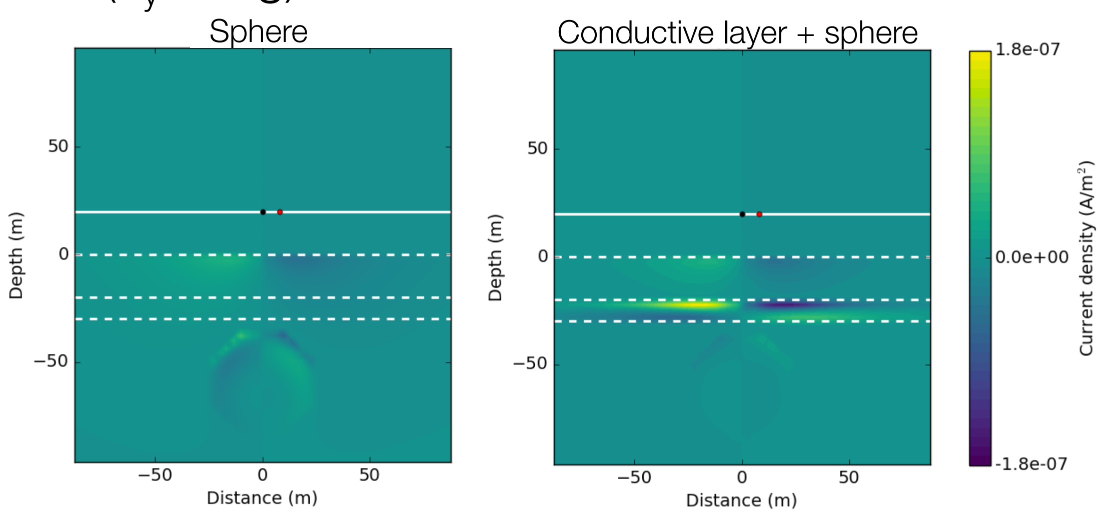
Resistivity models (thin **conductive** layer)



B_z sounding curves

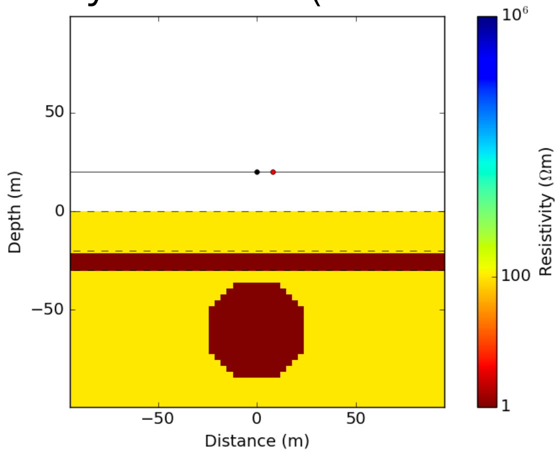


Currents (J_y imag)

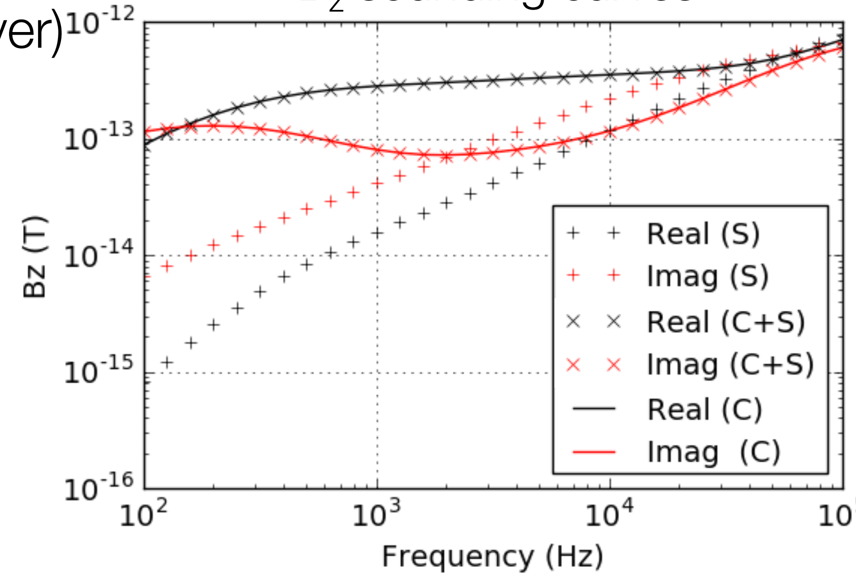


Shielding: EM with conductive layer

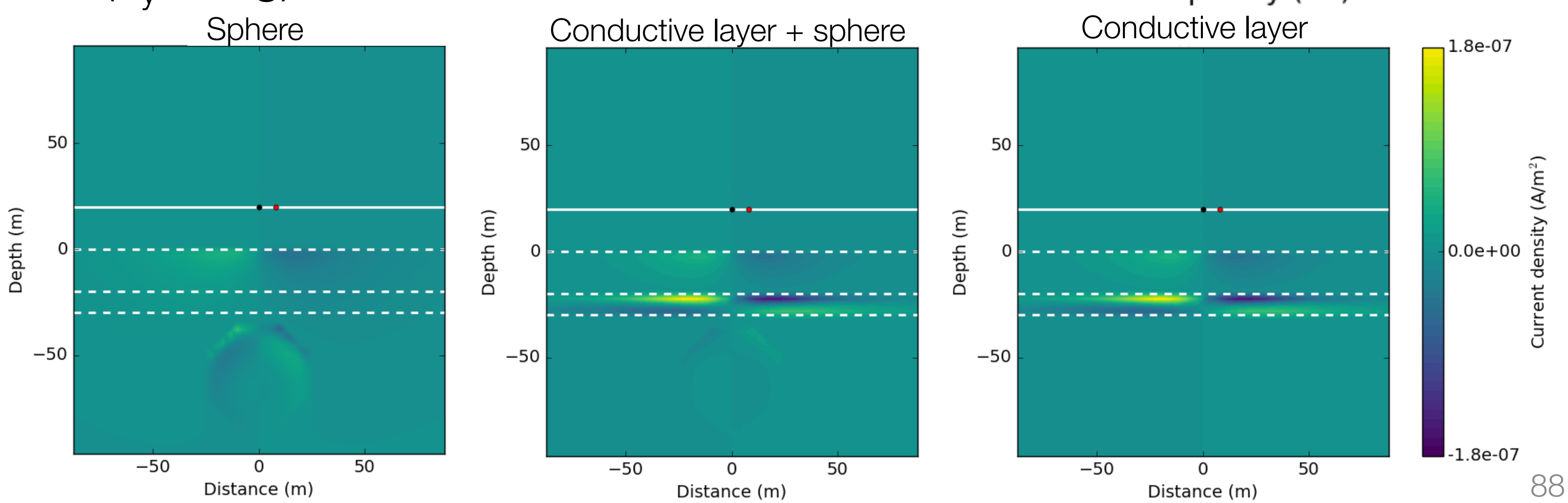
Resistivity models (thin **conductive** layer)



B_z sounding curves



Currents (J_y imag)



Outline

Setup

- Basic experiment
- Transmitters, Receivers

Time Domain EM

- Vertical Magnetic Dipole
- Propagation with Time
- Case History

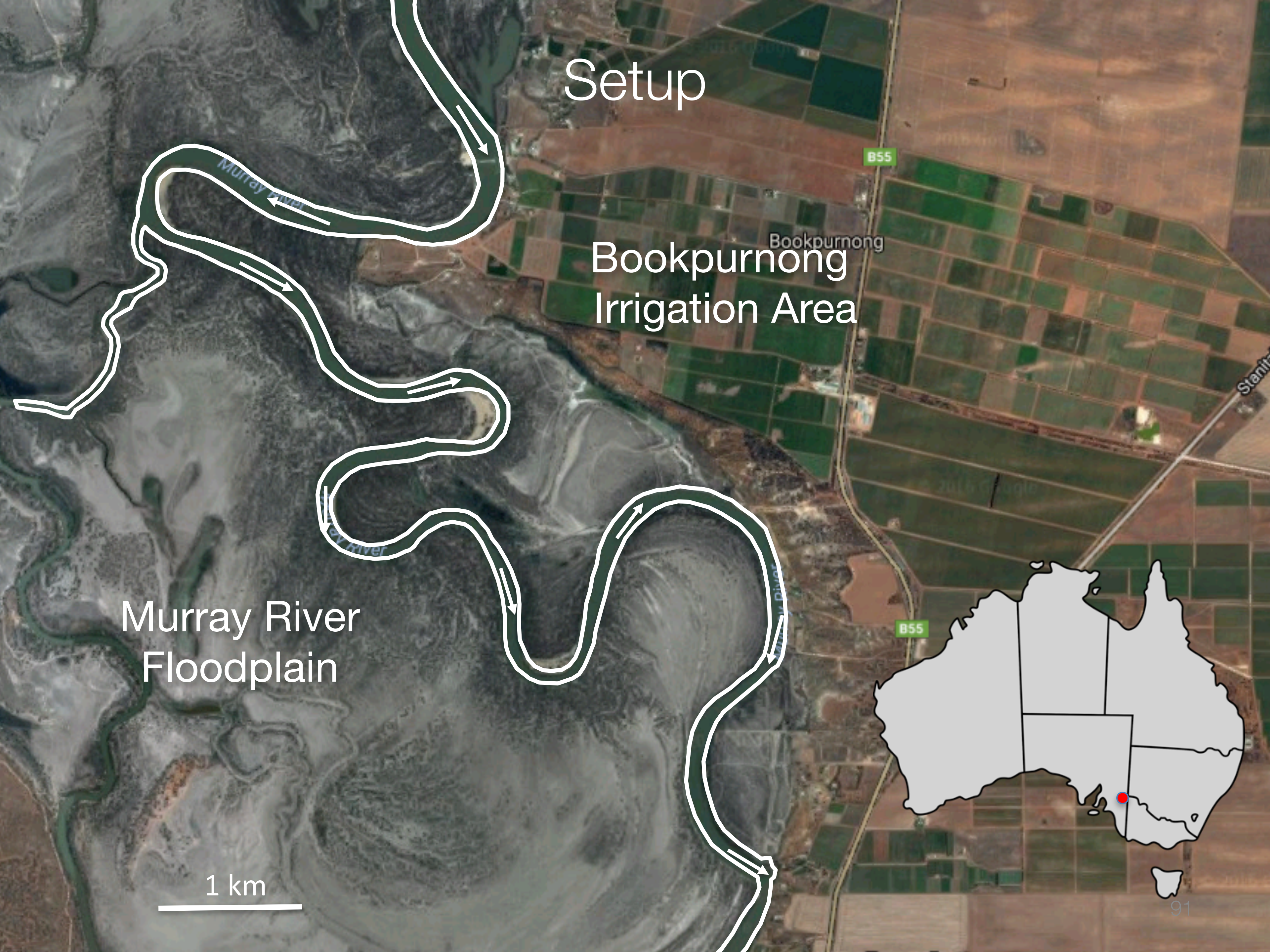
Frequency Domain EM

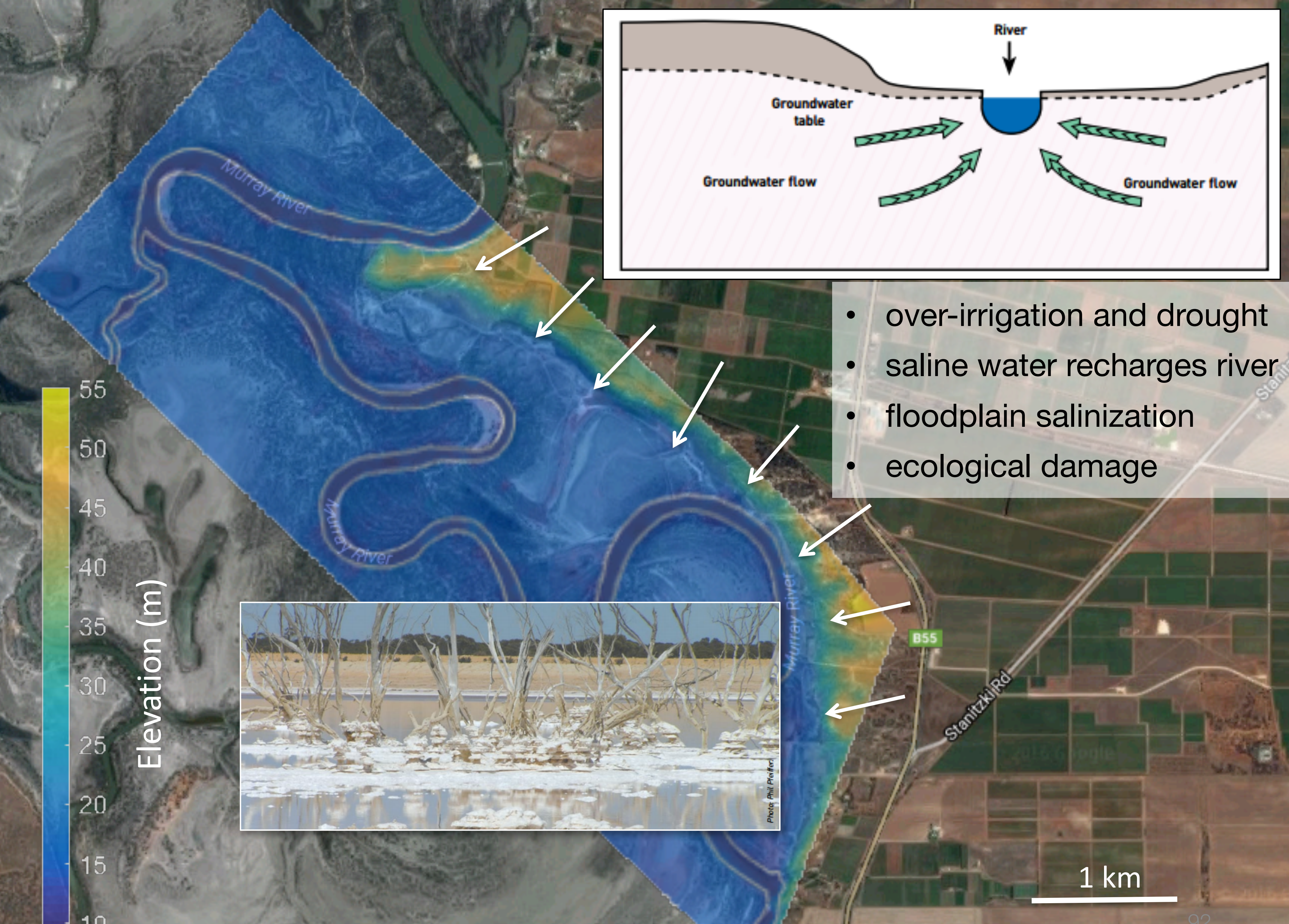
- Vertical Magnetic Dipole
- Effects of Frequency
- Case History – Groundwater

Questions

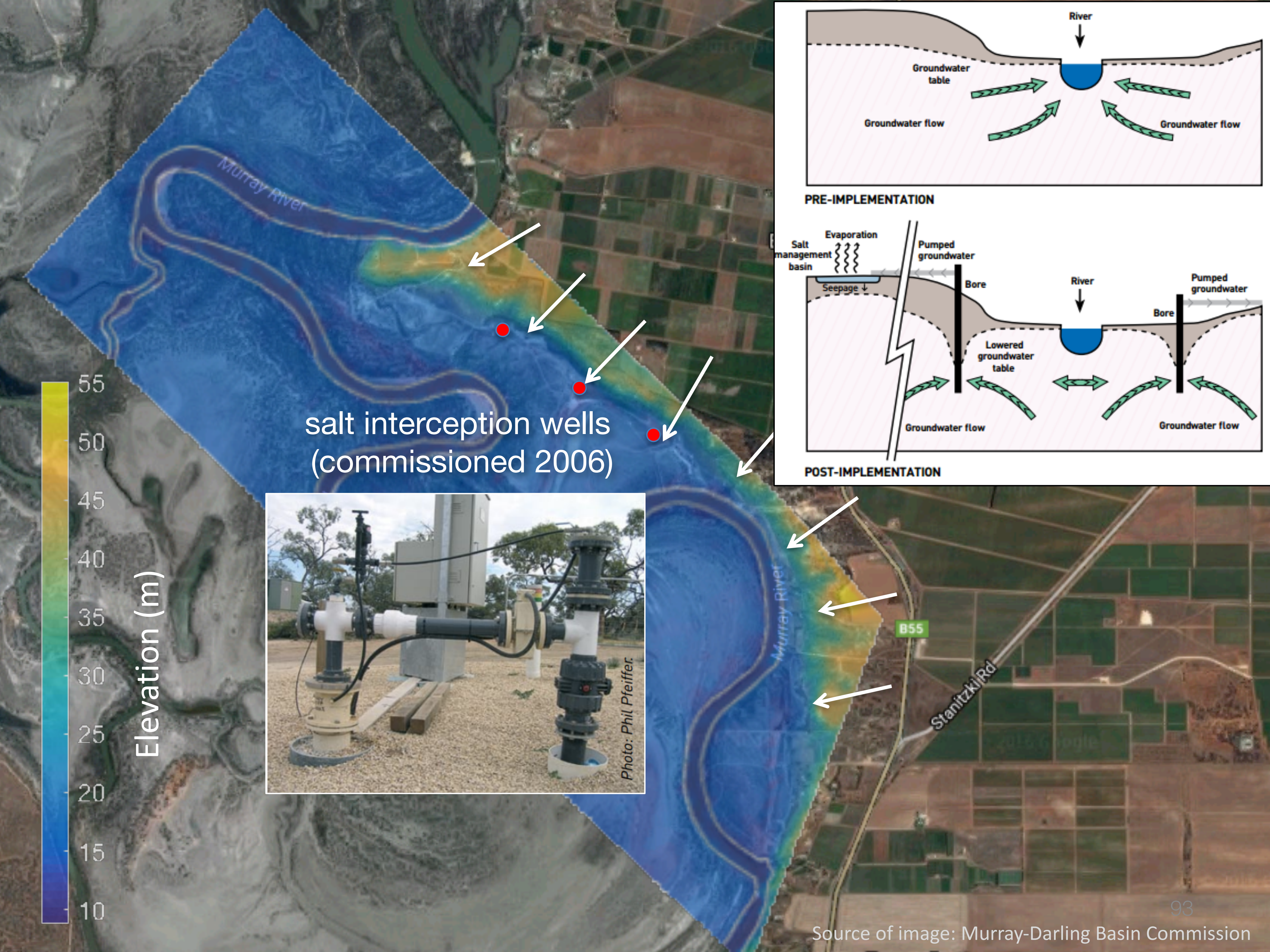
Case History: Bookpurnong

Viezzoli et al., 2009

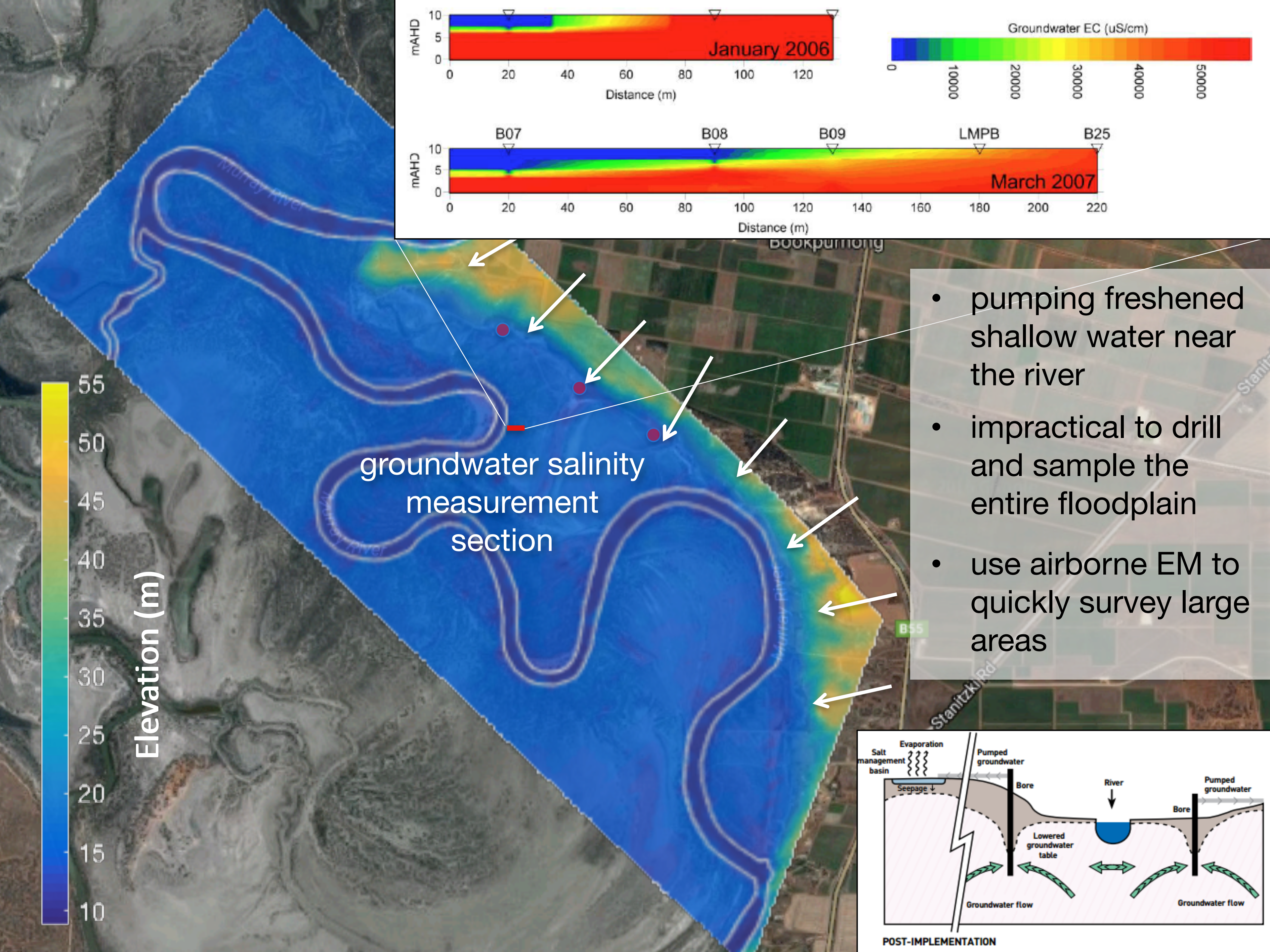

Setup
Bookpurnong
Irrigation Area
Murray River
Floodplain
Bookpurnong
B55
B55
Murray River
1 km



Source of image: Murray-Darling Basin Commission



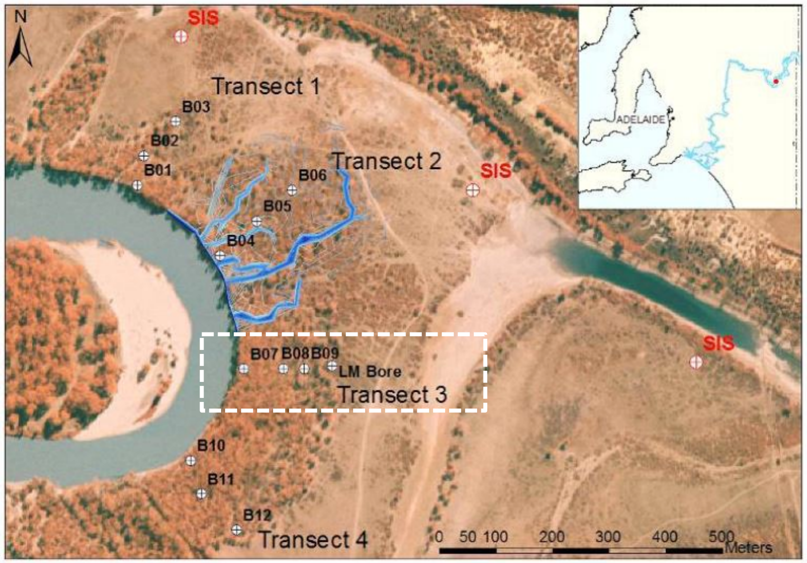
Source of image: Murray-Darling Basin Commission



mAHD
10
5
0
January 2006
0
20
40
60
80
100
120
Distance (m)
Groundwater EC (uS/cm)
0
10000
20000
30000
40000
50000
B07
B08
B09
LMPB
B25
March 2007
140
160
180
200
220
Bookpurnong
55
50
45
40
35
30
25
20
15
10
Elevation (m)
groundwater salinity measurement section
• pumping freshened shallow water near the river
• impractical to drill and sample the entire floodplain
• use airborne EM to quickly survey large areas
Salt management basin
Evaporation
Seepage
Pumped groundwater
Bore
River
Lowered groundwater table
Groundwater flow
POST-IMPLEMENTATION

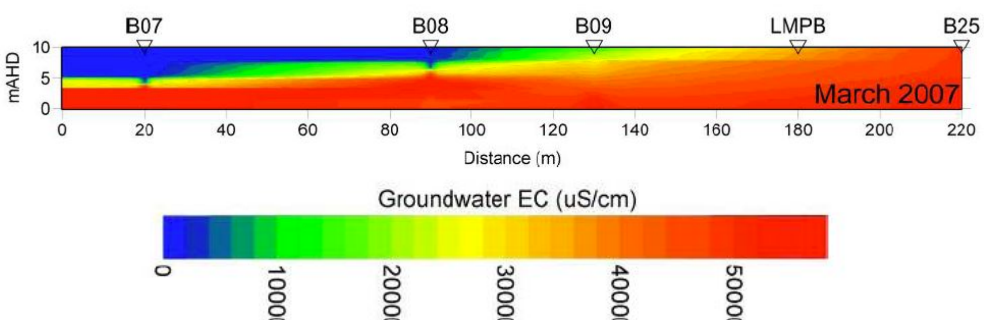
Properties

Location map for salinity measurements



Unit	Conductivity
Saline water	High, 3 - 5 S/m
Fresh water	Low, 0.01 S/m

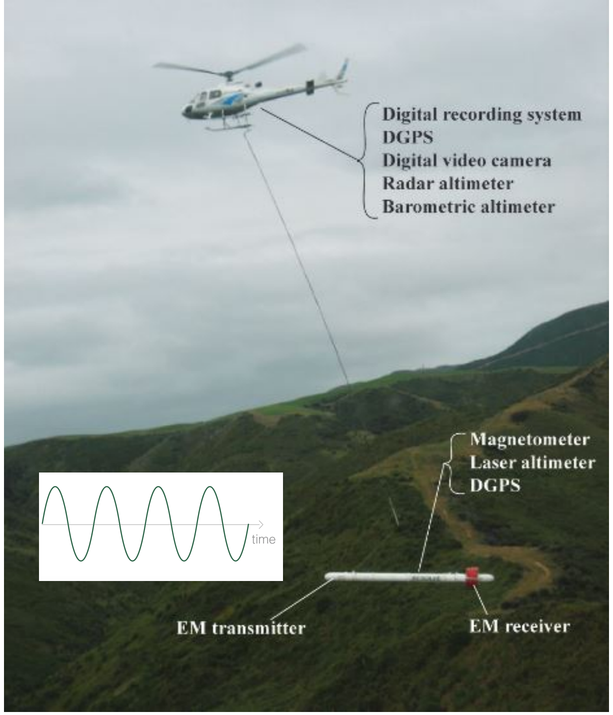
Conductivity from salinity measurements



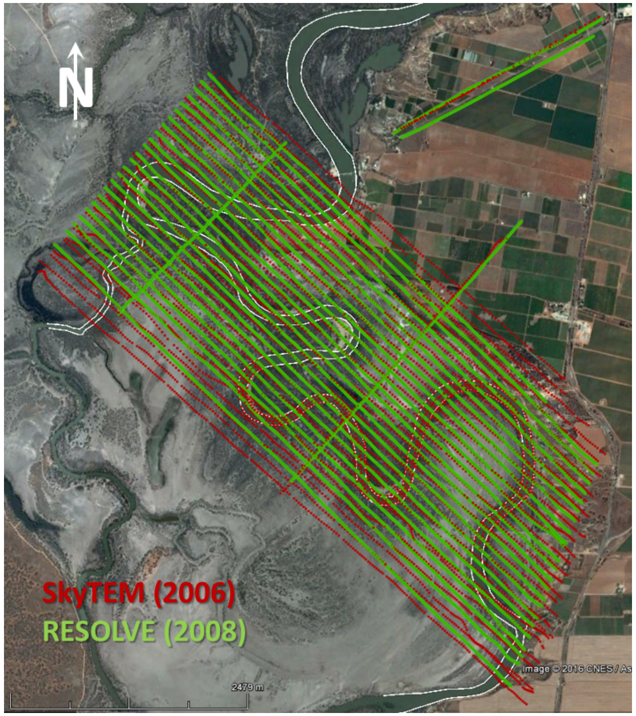
Holland et. al., 2008.

Survey

Resolve system (2008)

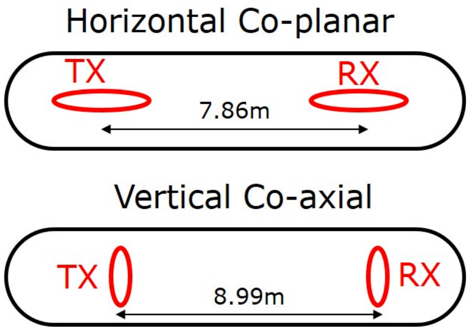


Flight lines



Horizontal Co-planar (HCP) frequencies:
- 382, 1822, 7970, 35920 and 130100 Hz

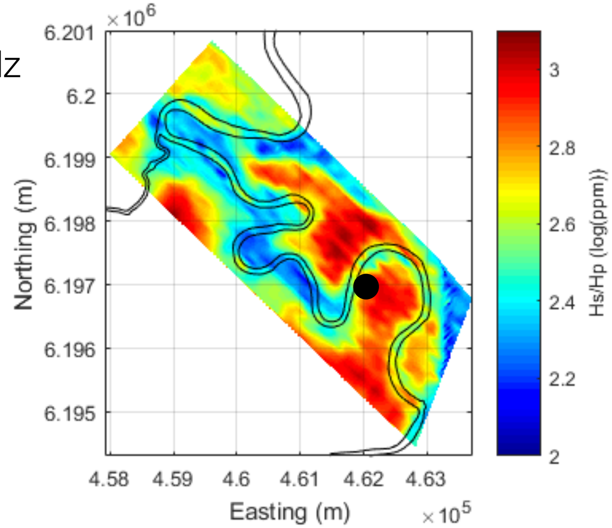
Vertical Co-axial (VCA) frequencies:
- 3258 Hz

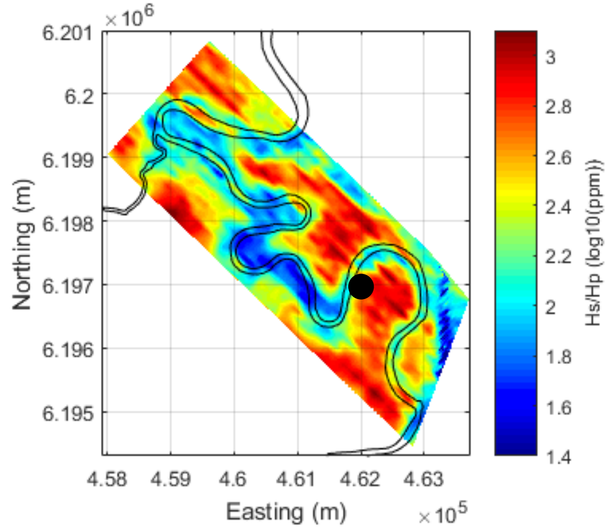


Horizontal Co-planar (HCP) data

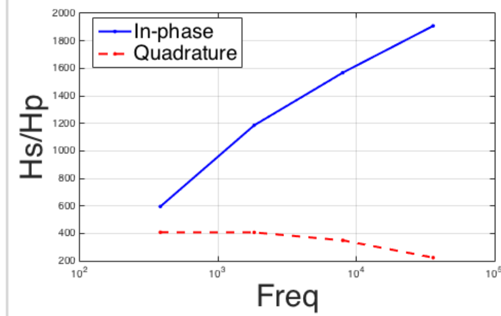
In-Phase (Real) | Quadrature (Imaginary)

382 Hz

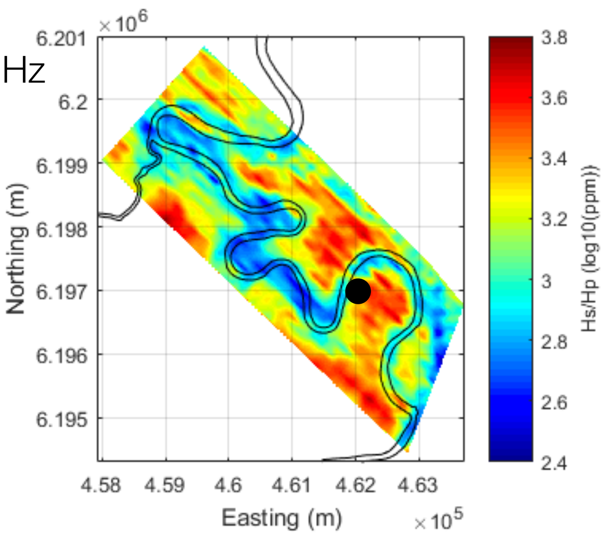


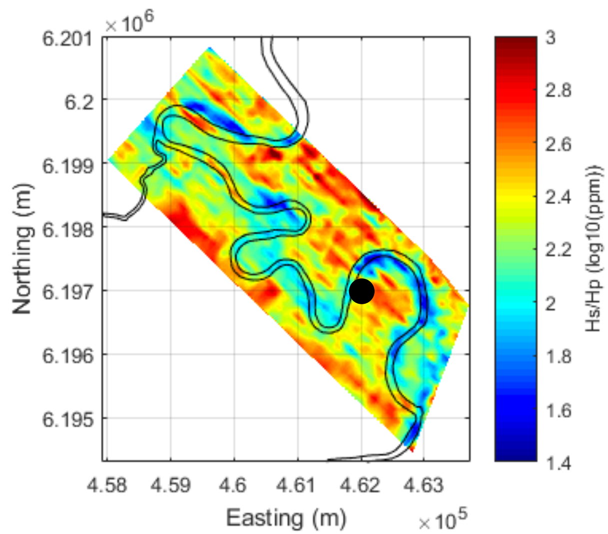


Sounding curve

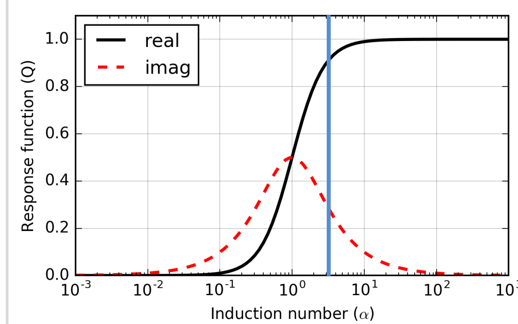


35920 Hz



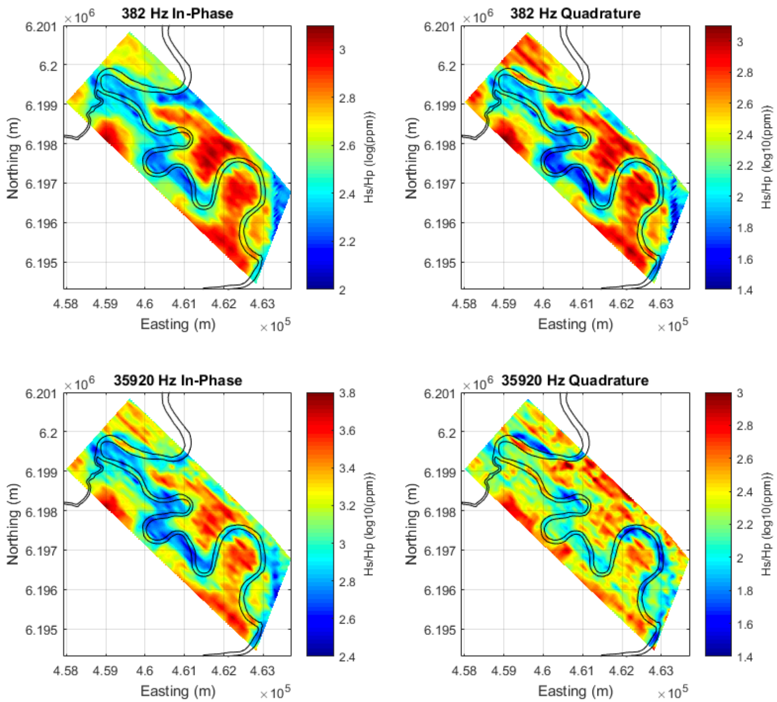


Response curve

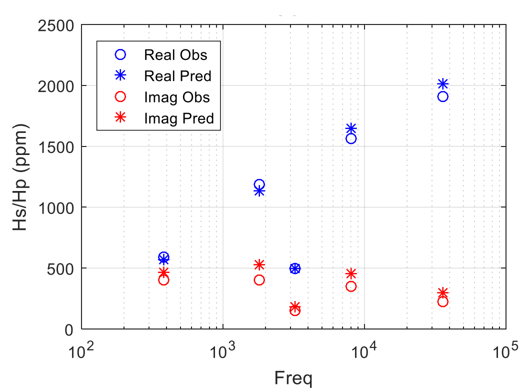


Processing: 1D inversion

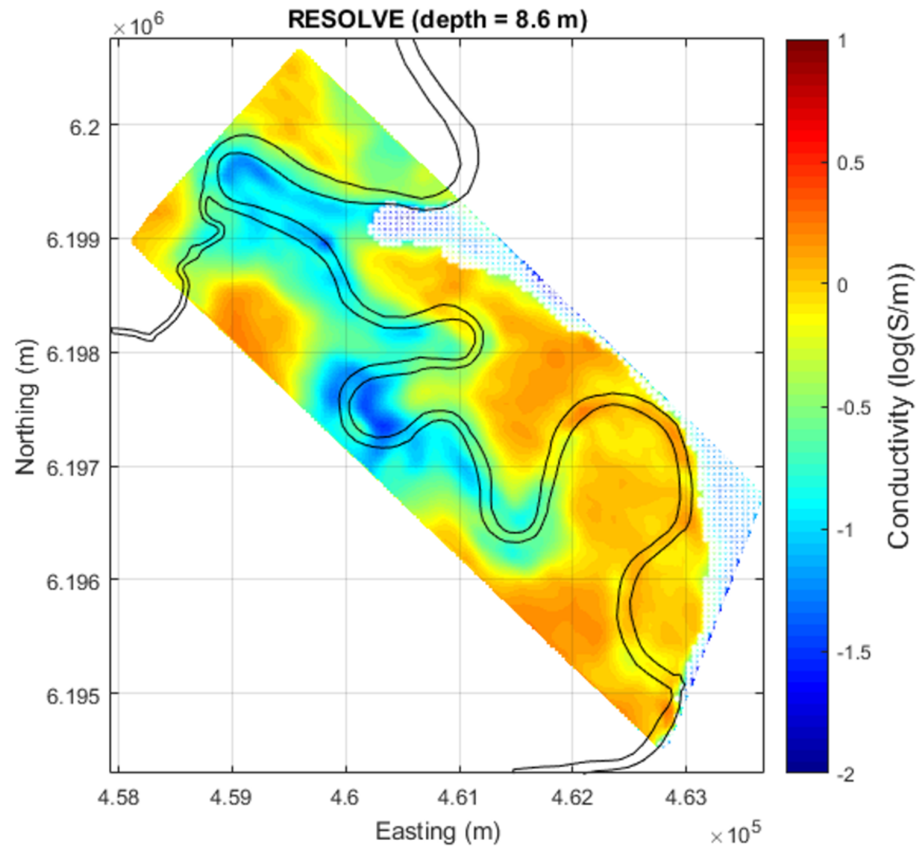
Data



Data fit

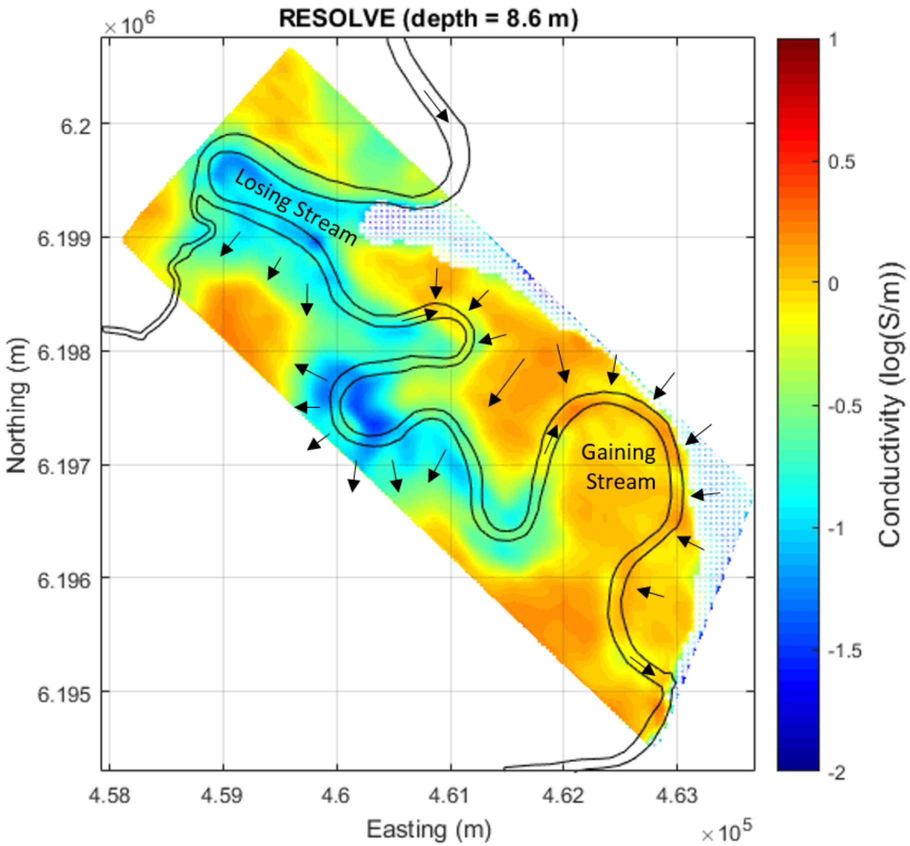


Conductivity model (stitched)

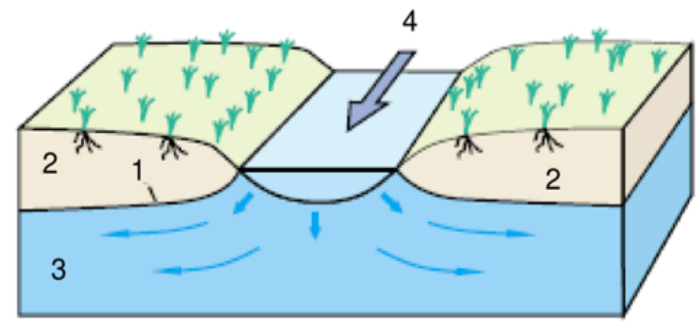


Interpretation

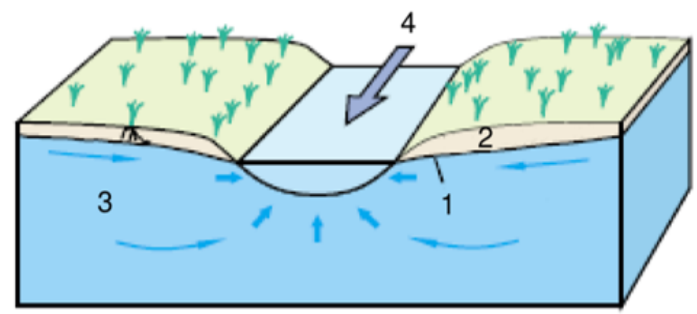
Conductivity model (stitched)



Losing Stream



Gaining Stream

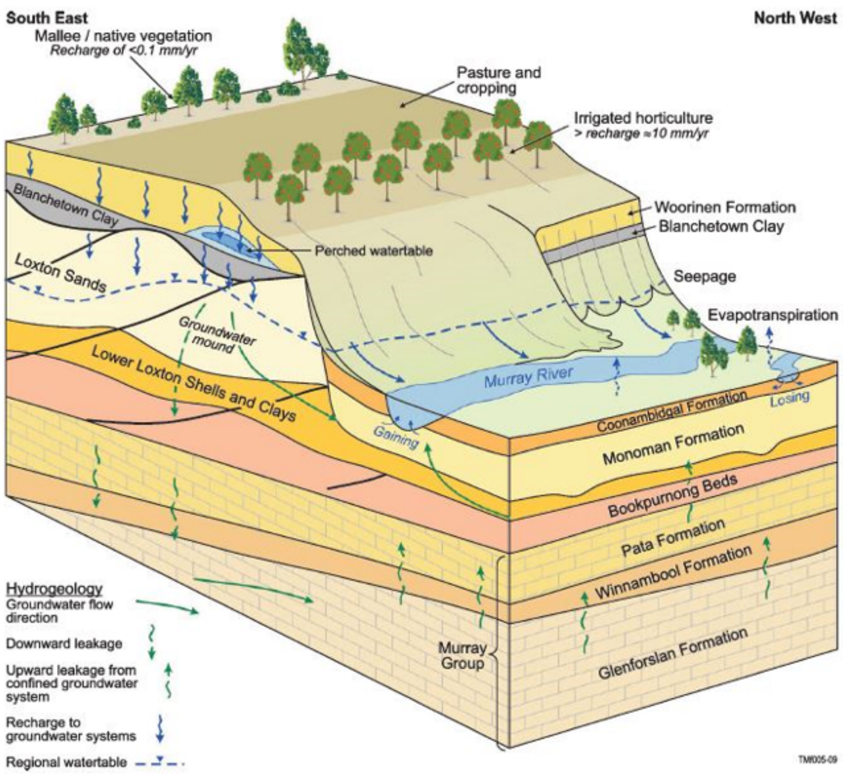


1 – Water table 2 – Unsaturated zone

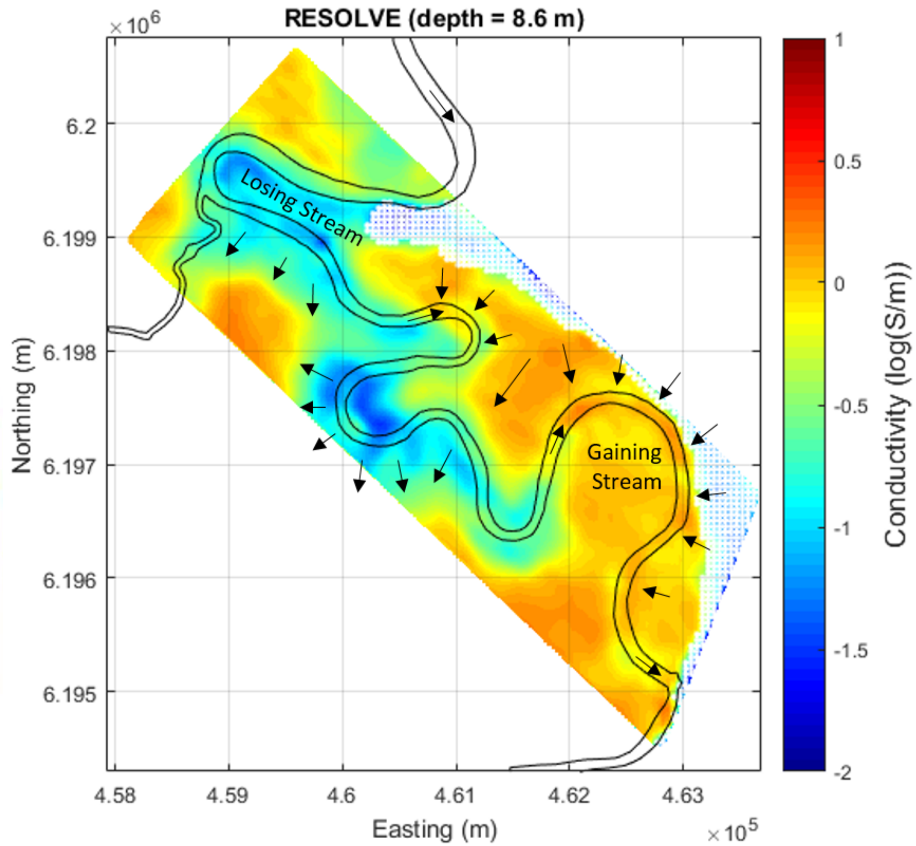
3 – Saturated zone 4 – Flow direction

Synthesis

Hydrological model

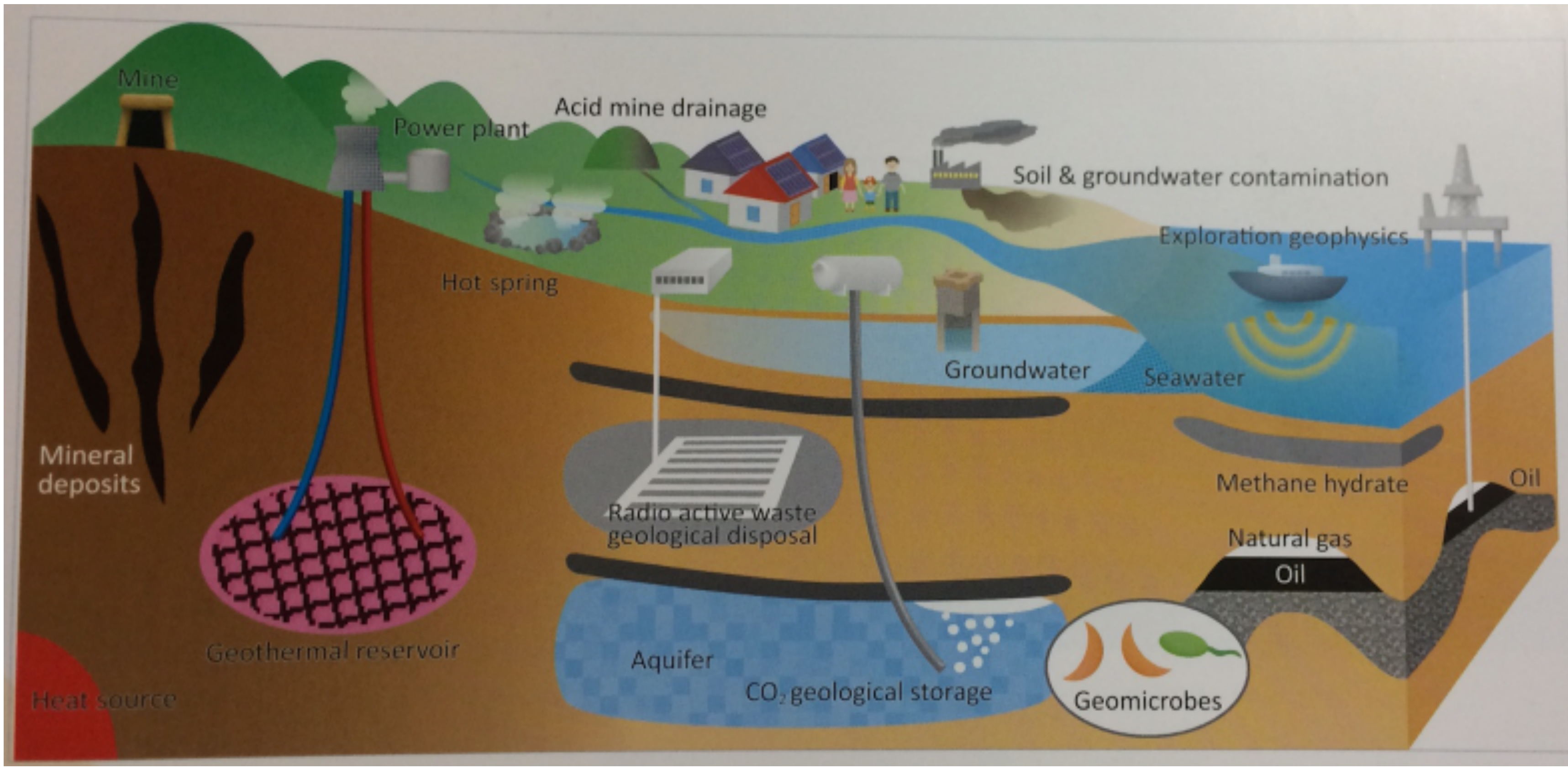


Conductivity model (stitched)



An example from DISC Tokyo

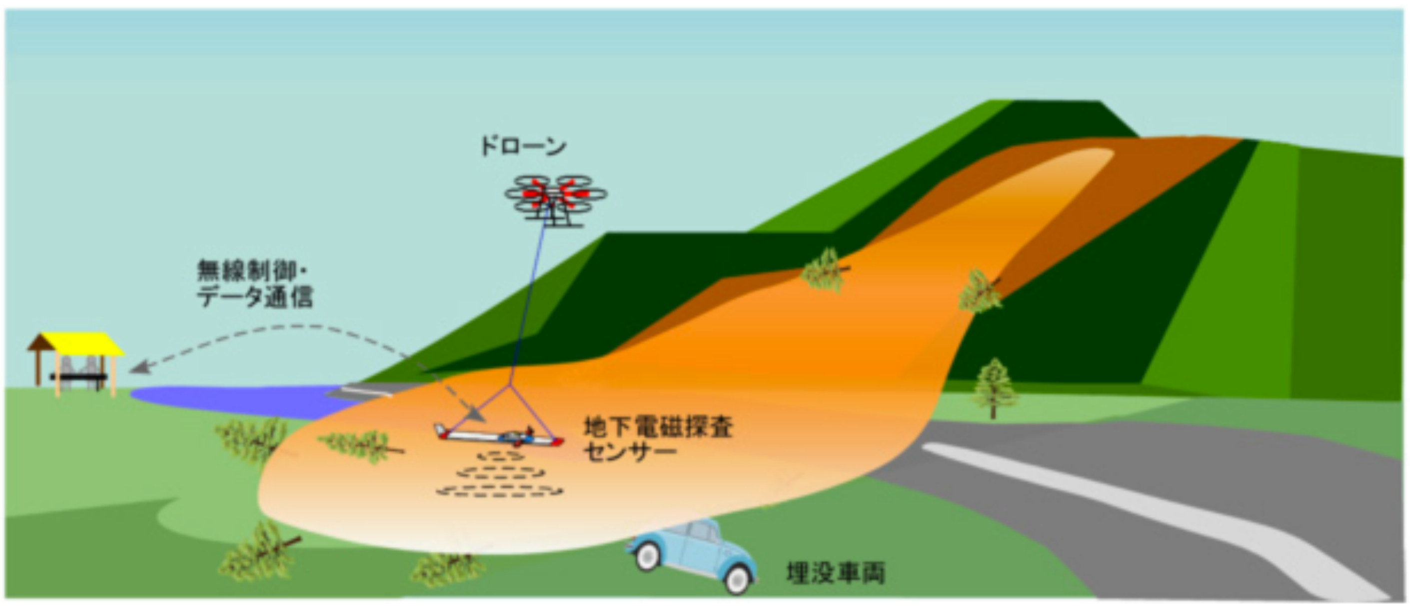
DISC Tokyo…


Mine
Power plant
Acid mine drainage
Soil & groundwater contamination
Exploration geophysics
Hot spring
Groundwater
Seawater
Mineral deposits
Methane hydrate
Oil
Radio active waste geological disposal
Natural gas
Oil
Geothermal reservoir
Aquifer
CO_2 geological storage
Geomicrobes
Heat source

EM Geophysics using Drone Technology: AIST

Setup:

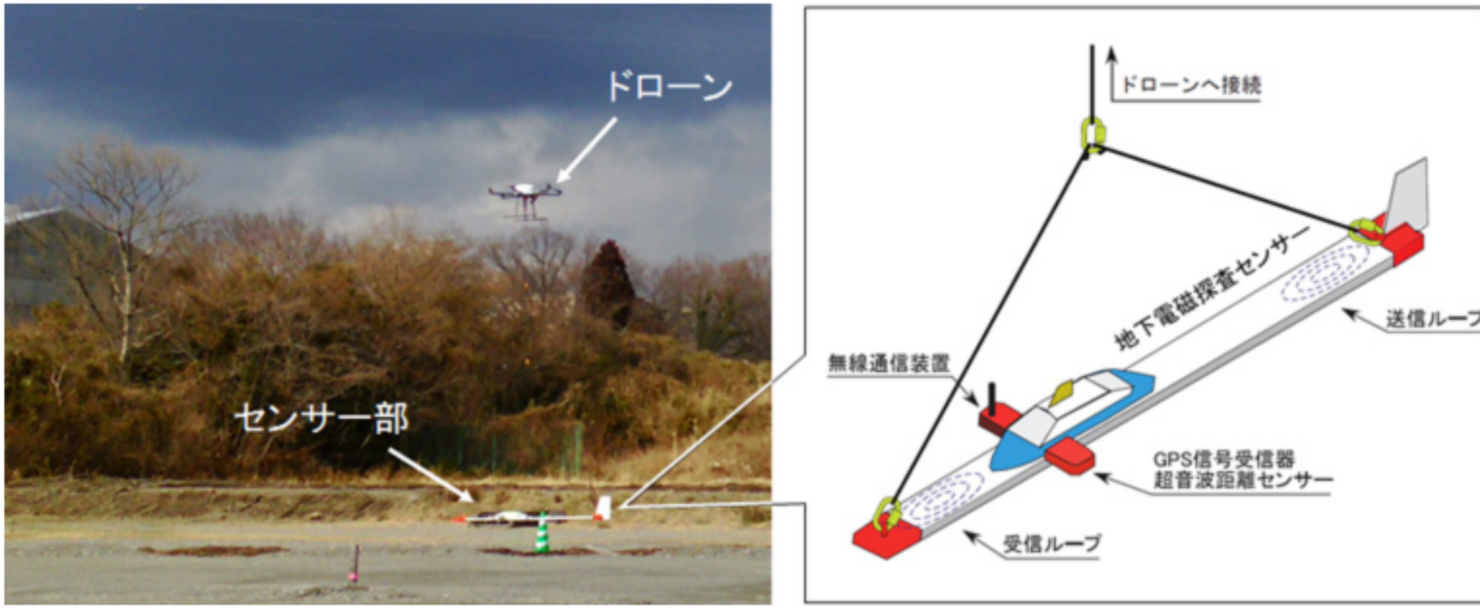
- Develop FDEM system for a drone
- Application: near surface geophysics problems
- Example: find automobiles buried in a landslide



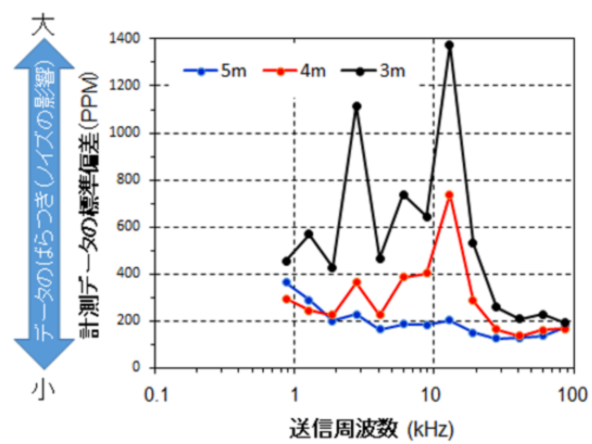
Exploration image of buried vehicles at the site of sediment-related disasters by developed system

Survey equipment

Drone EM system



- System must be removed from the noise of the drone
- Sensor located 5 meters below drone



Data acquisition

System must be close to the ground
(primary field $1/r^3$)

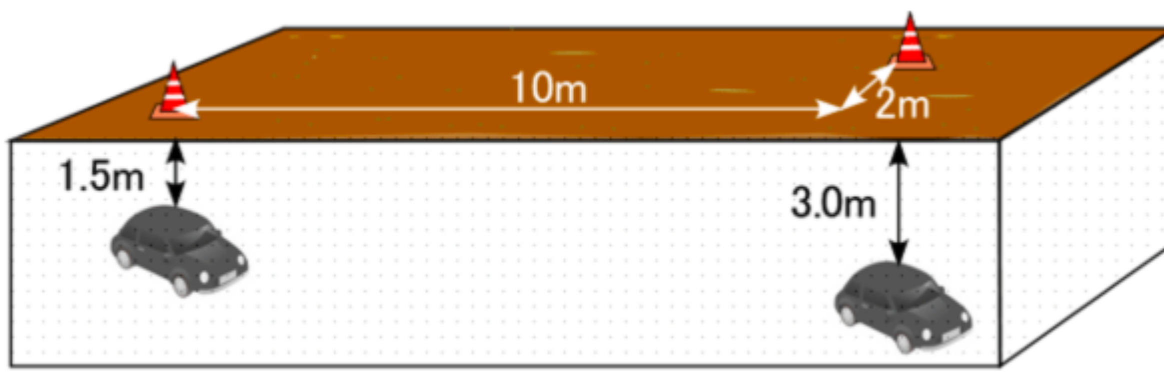


Fig. 4 Arrangement of the burial vehicle experiment site of the construction laboratory site
Two buried mini vehicles are buried in the ground of 1.5 m depth and 3.0 m depth, respectively.

Data and interpretation

- In-phase and quadrature phase data recorded at multiple frequencies.
- Metallic objects have high induction number
- Signal is mostly in the In-phase part
- Plot amplitude: both cars imaged

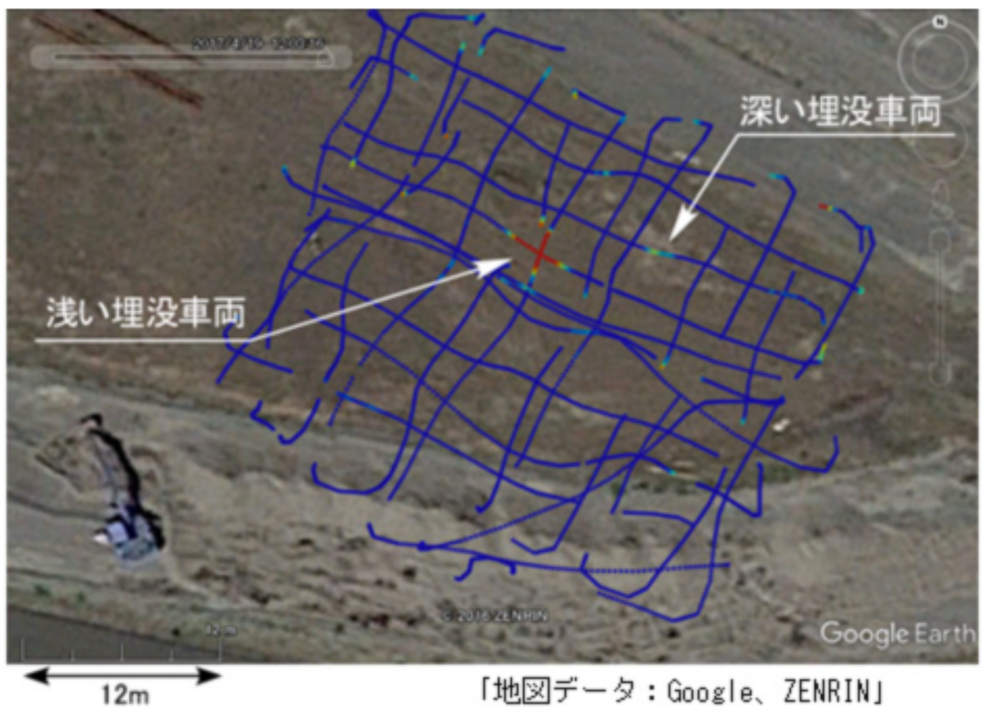


Fig. 6 Exploration data by precision drone navigation measurement (measurement frequency 60 kHz)

Additional Material

- Case Histories:
    - Lalore (Minerals)
    - West Plains (Minerals)
    - La Magdalena (Minerals)
    - Austria (Landslides)

- Tutorial on UXO
    - Case History: Pole Mountain (UXO)

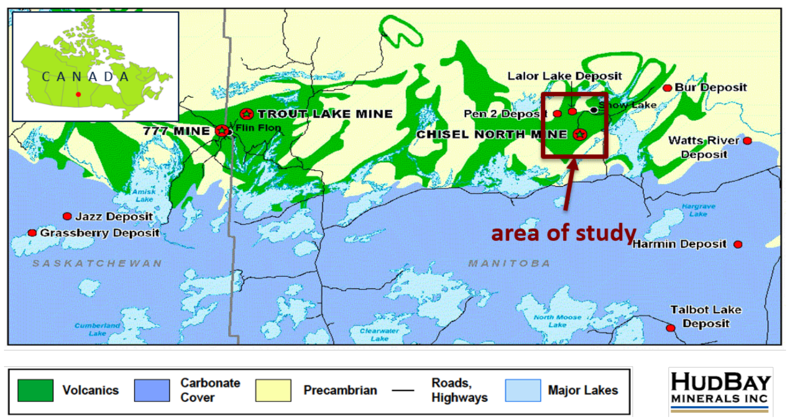
Case History: HeliSAM at Lalore

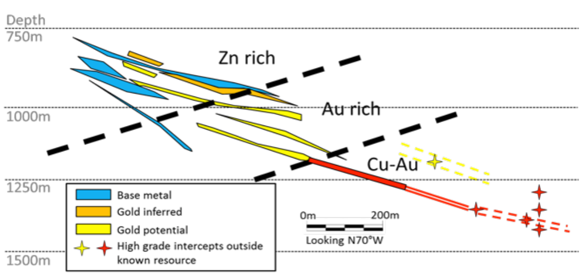
Yang & Oldenburg, 2016

Setup

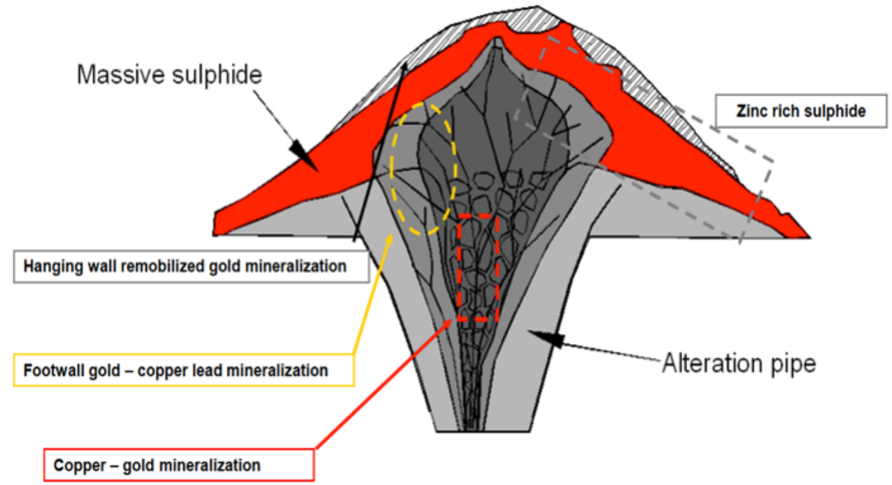
Geological framework

- Zinc-rich massive sulfides (Cap)
- Cu-Au sulfides: (stringers) within pipe
- Disseminated sulfides around deposit





Typical cross-section

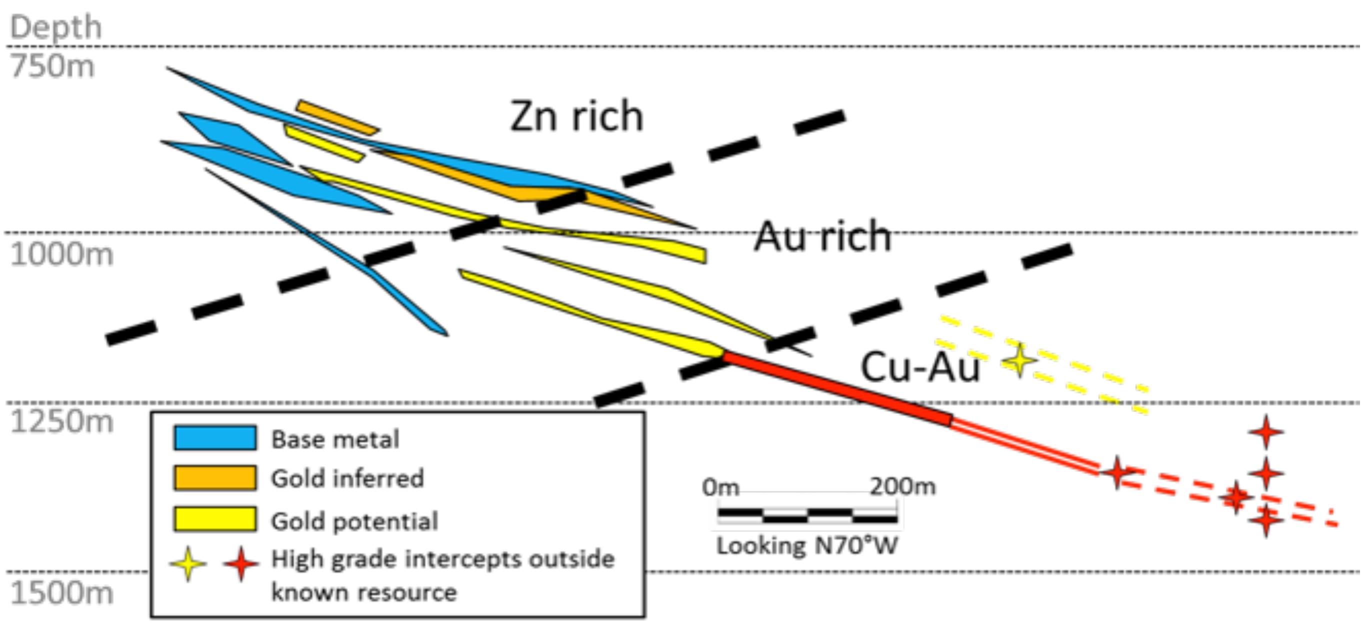


Goal:

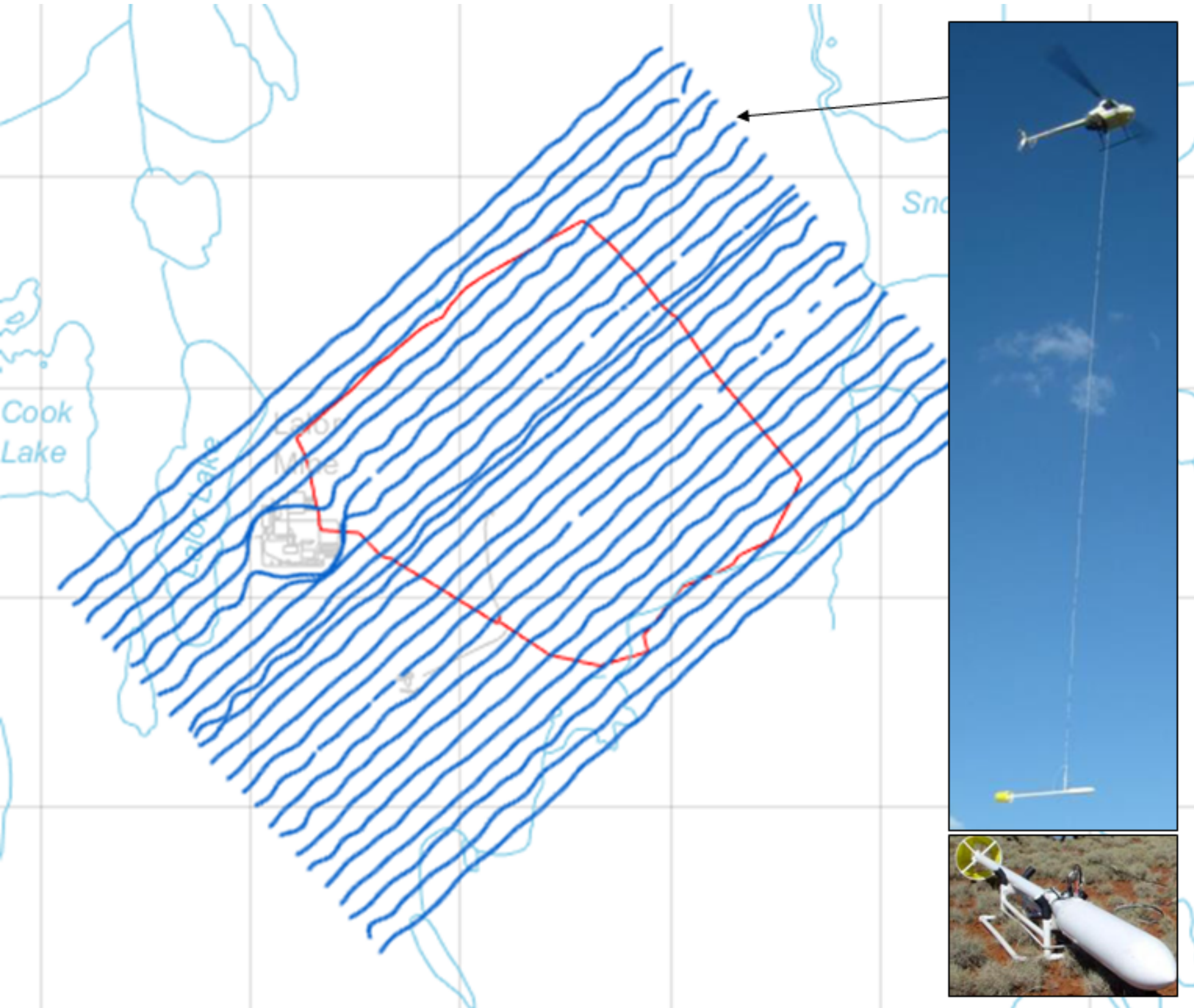
- Find deposits
- TDEM to find deeper off-hole targets

Properties

Rocks/minerals	Resistivity
volcanics	~1000 Ωm
sulfides	~ 1 Ωm



Survey: HeliSAM



Transmitter: (Red)

- Ground loop (~2km)
- Waveform: 7.5 Hz, 50%
- Ramp turn-off 0.4ms

Receiver:

- Cesium Vapor Mag
- 16 Time Ch: 0.42-27 ms

Flight lines: (Blue)

- 100 m spacing,
- Data every 5 m

Data

- Measure total field

$$\mathbf{B} = \mathbf{B_0} + \mathbf{B_a} + \mathbf{B_{em}}$$

earth's magnetic field

anomalous earth's field

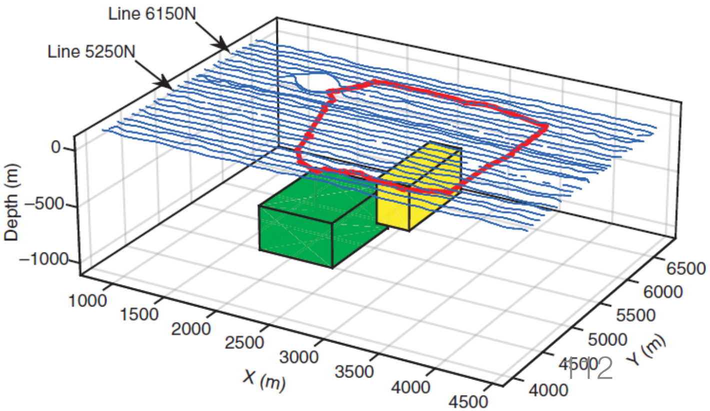
induced EM field

- Project secondary fields onto $\hat{\mathbf{B}}_0$

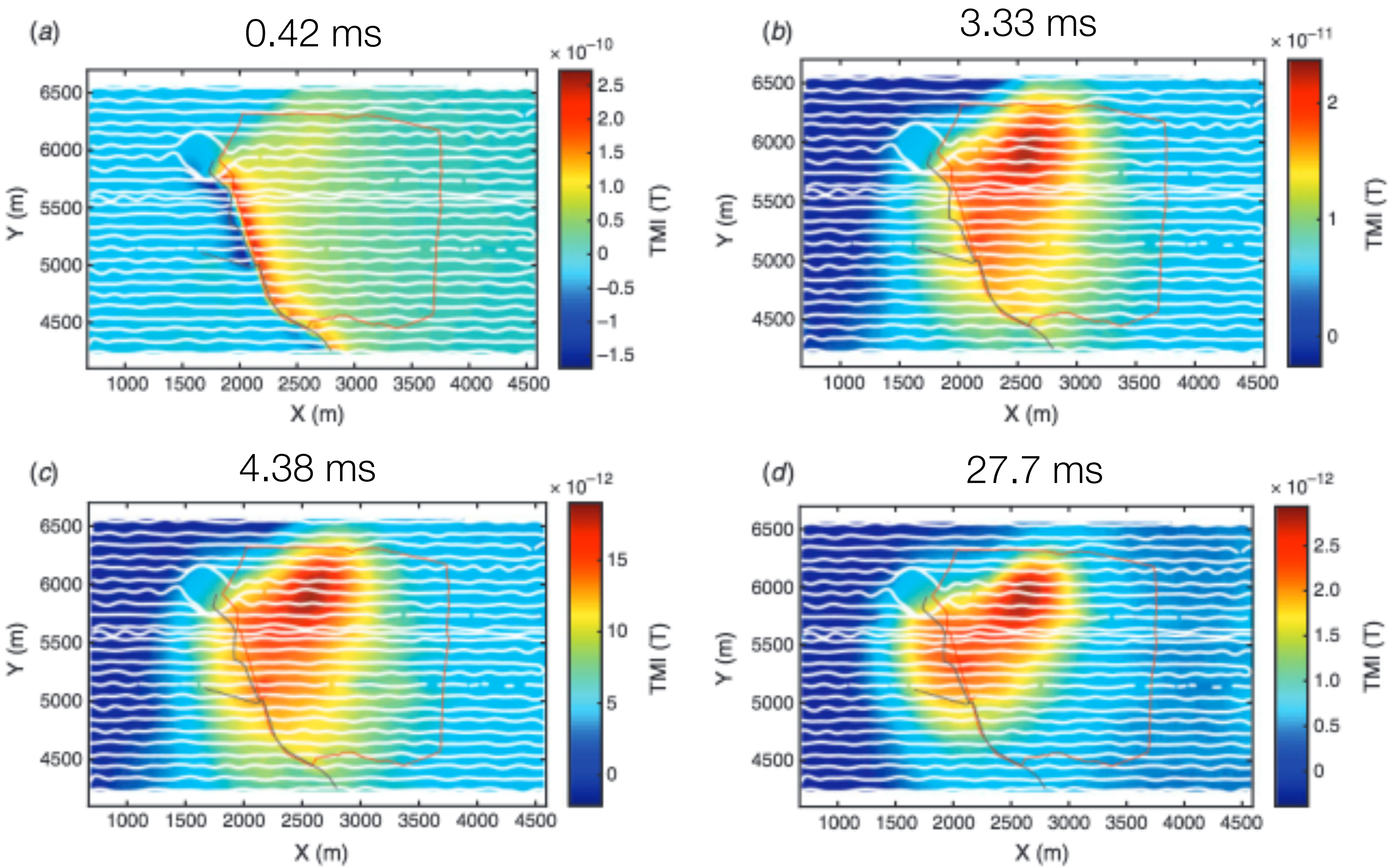
$$\Delta|\mathbf{B}| = |\mathbf{B_0} + \mathbf{B_a} + \mathbf{B_{em}}| - |\mathbf{B_0}|$$
$$\approx (\mathbf{B_a} + \mathbf{B_{em}}) \cdot \hat{\mathbf{B}}_0$$

- Change polarity on TX
- Subtract to obtain HeliSAM data

$$\Delta|\mathbf{B}| \approx \mathbf{B_{em}} \cdot \hat{\mathbf{B}}_0$$

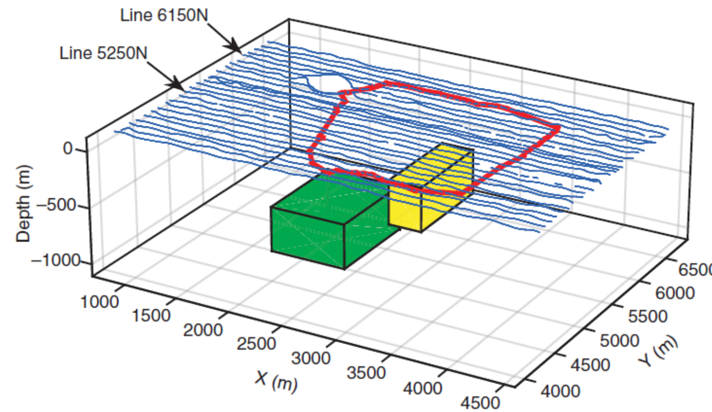


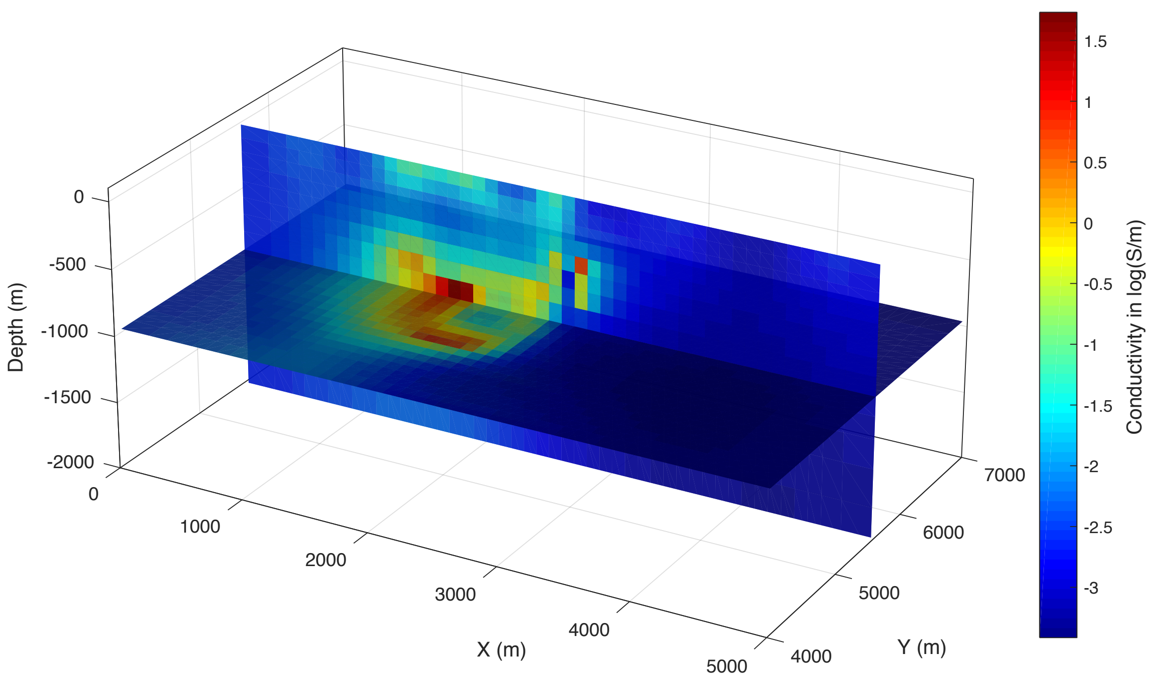
Data



Processing: Inversion of Late Time Data

- Discard early time data
  - Contaminated by infrastructure
- Invert Time Ch 8-16 (4.44-28 ms)
- Inversion needs a "warm start"
  - Maxwell used to generate 2 prisms





- Image deep structure

Processing: Inversion of Late Time Data

- Discard early time data
  - Contaminated by infrastructure
- Invert Time Ch 8-16 (4.44-28 ms)
- Inversion needs a "warm start"
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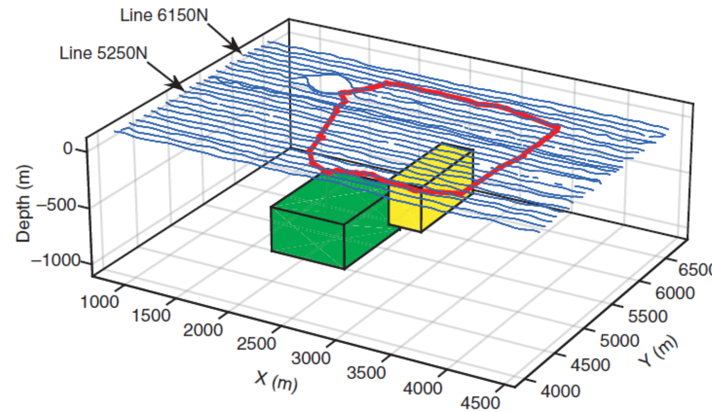
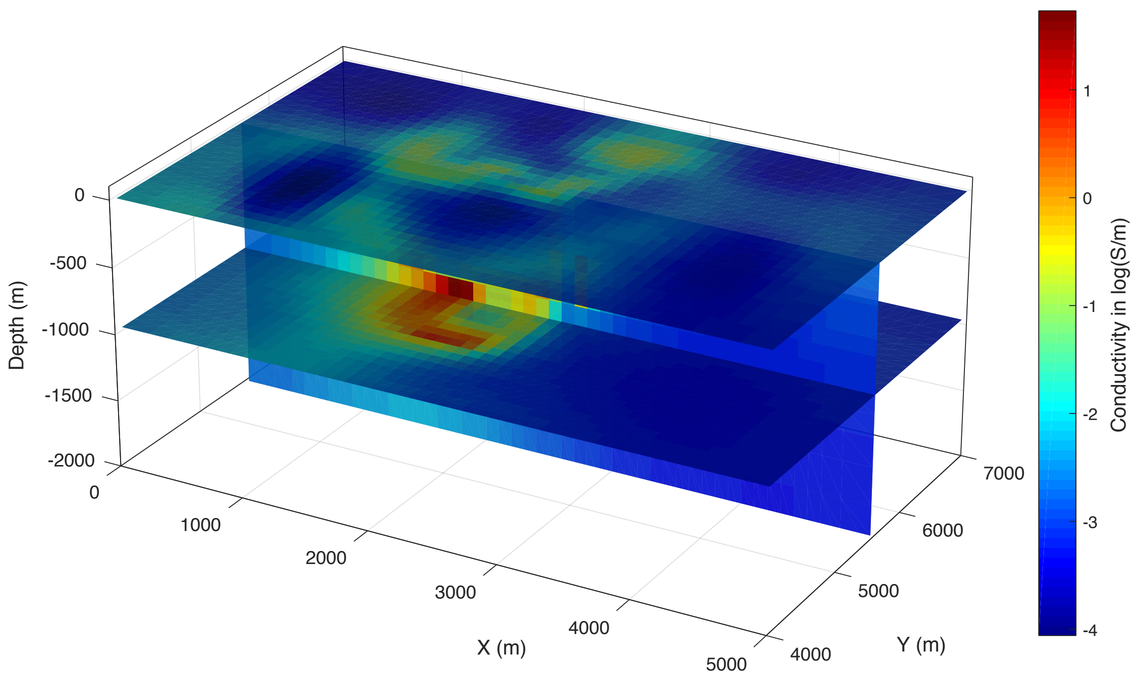
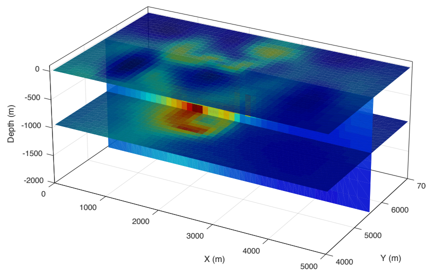




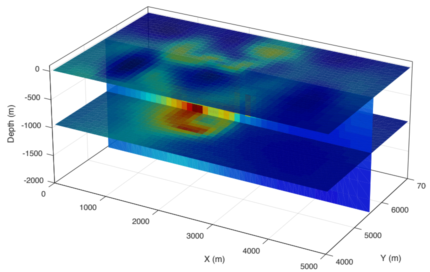
- Image deep structure
- See near surface conductive features

Processing: Inversion of Early Time Data



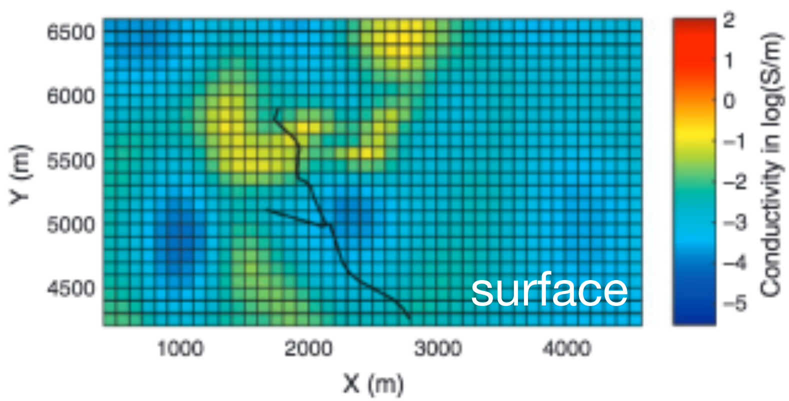
- Late-time inversion sees deep structure
- Some conductive features near surface
- **What is the effect of throwing away the early time data?**

Processing: Inversion of Early Time Data



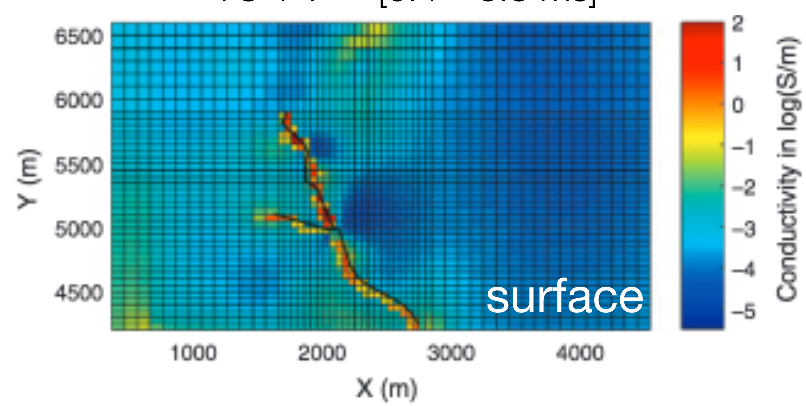
- Late-time inversion sees deep structure
- Some conductive features near surface
- **What is the effect of throwing away the early time data?**

Inverting late time data
TC 8 – 15 [4.4 – 28 ms]



- erroneous near surface structure

Inverting early time data
TC 1-7 [0.4 – 3.3 ms]

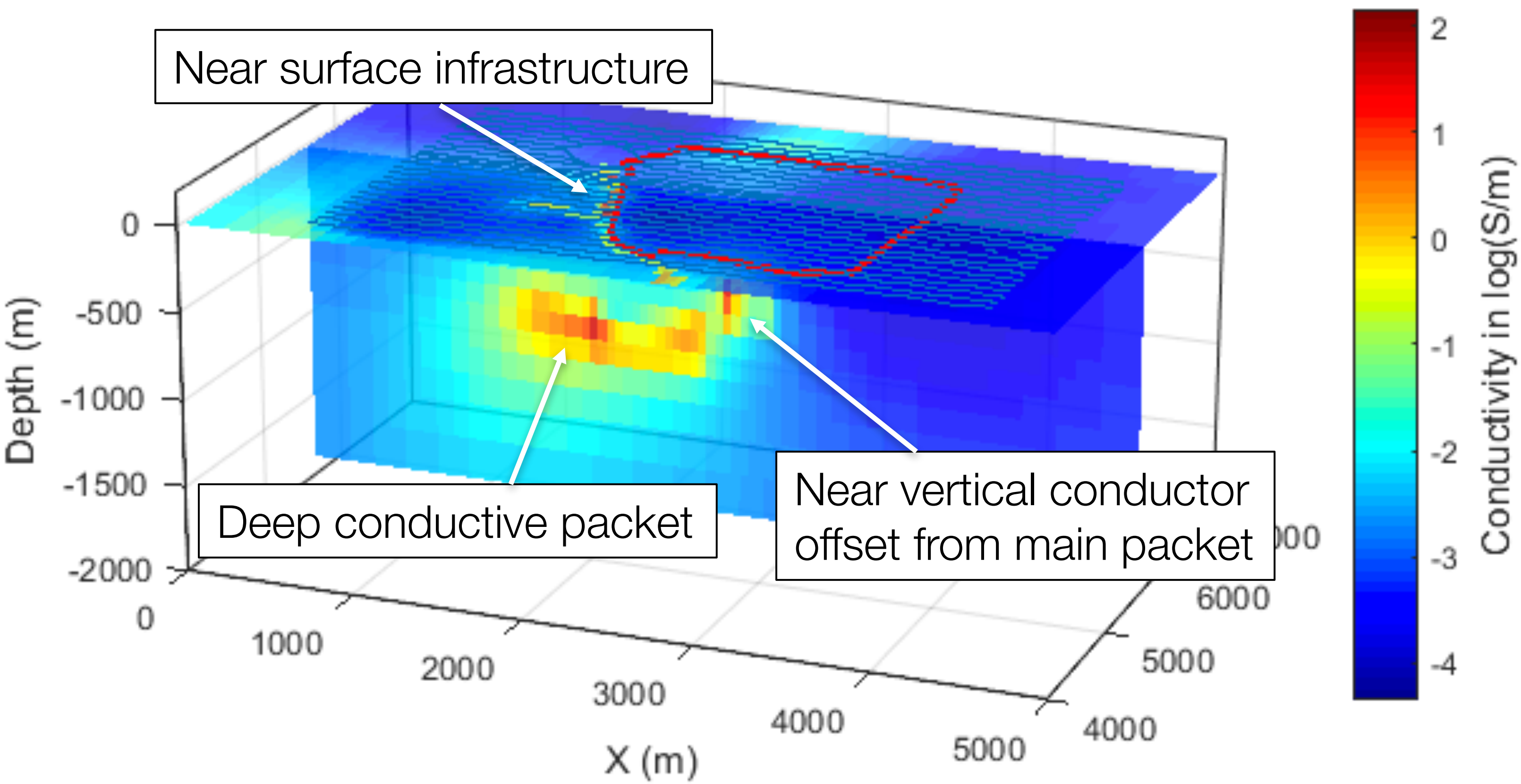


- information about infrastructure and near-surface conductivity

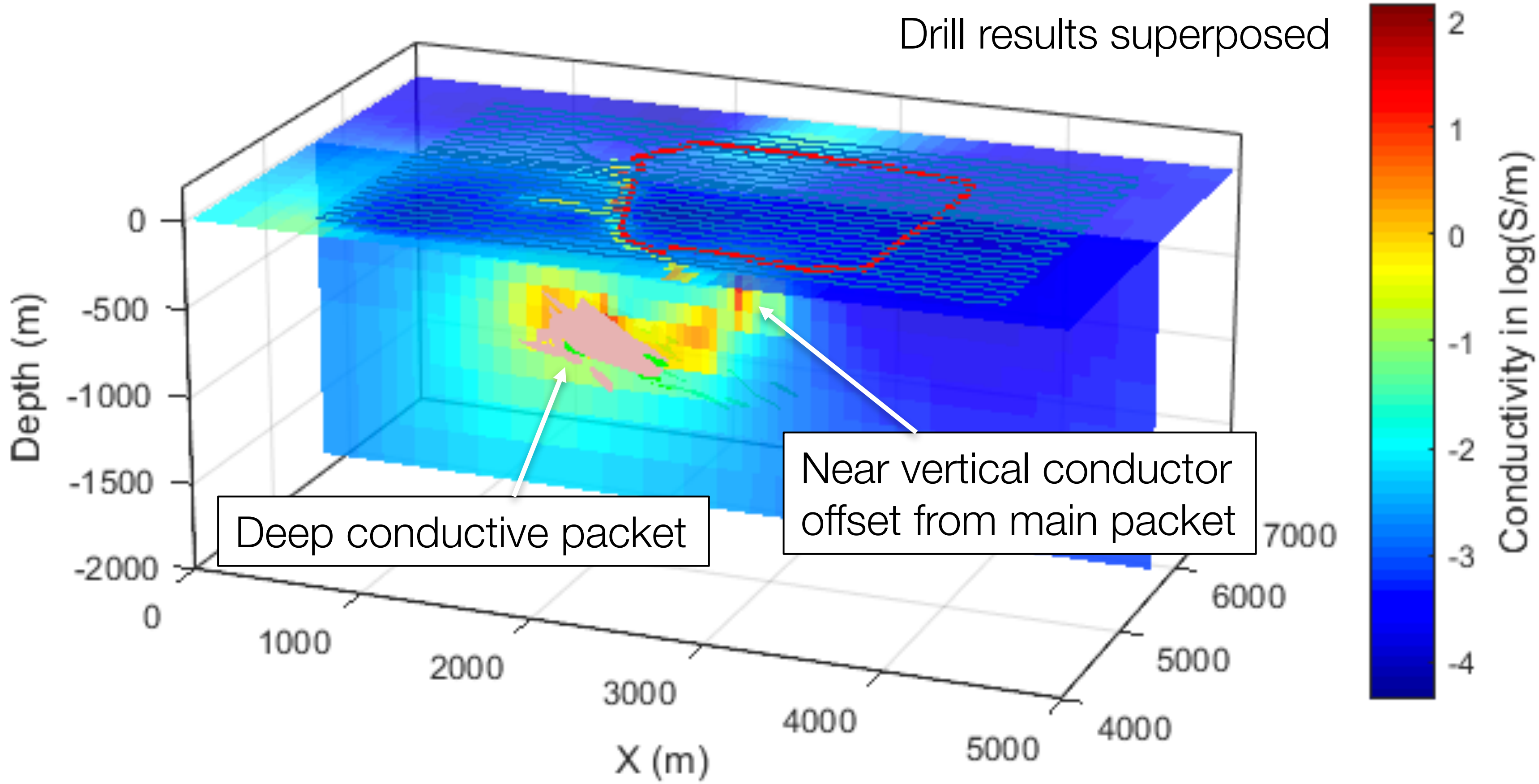
Processing: Inversion of all time channels

Starting and reference model:

- High conductivity from early time inversion
- Two conductive blocks

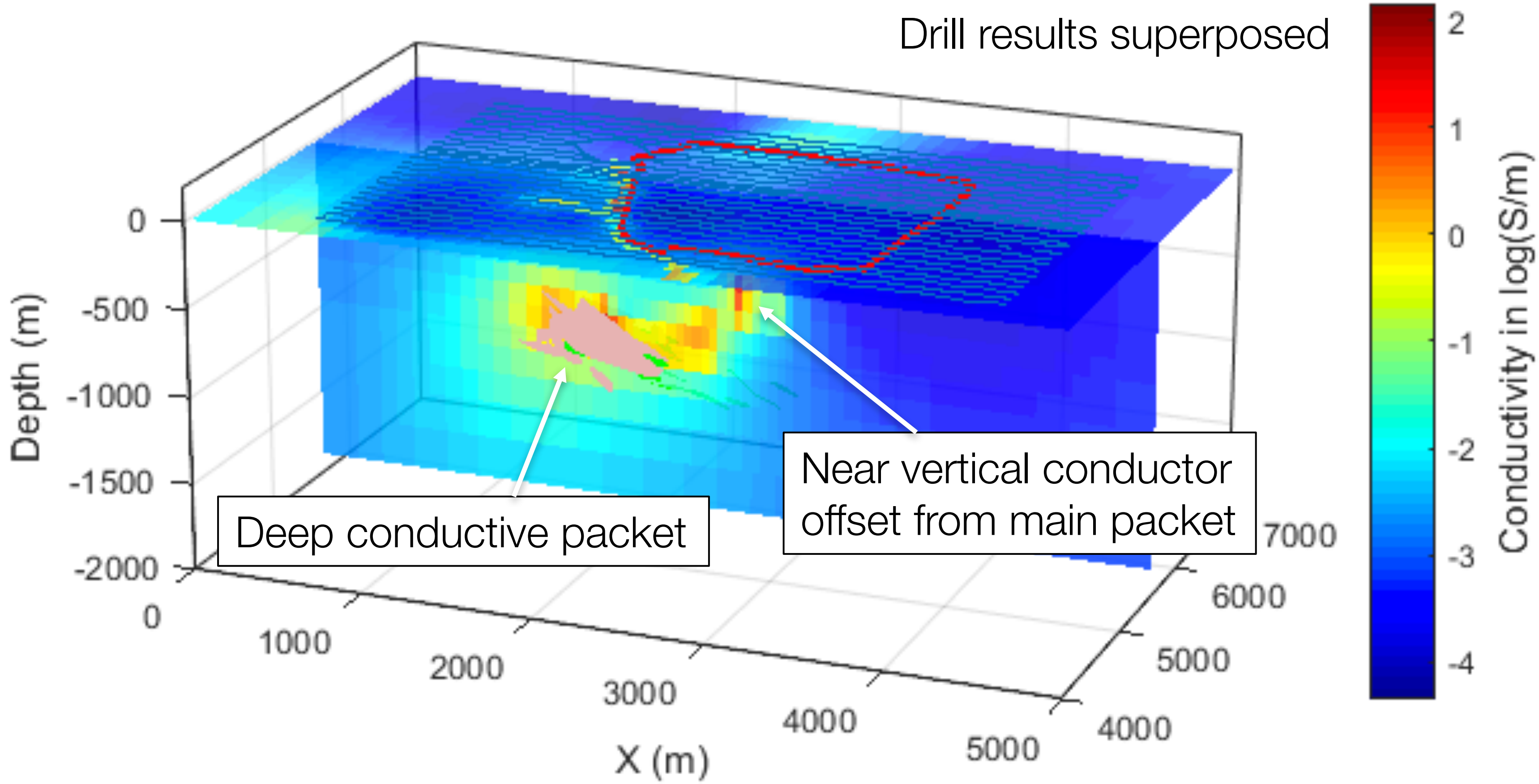


Synthesis



- Imaged main known conductive bodies
- Second conductor: recently drilled and contained sulfides (argillite)

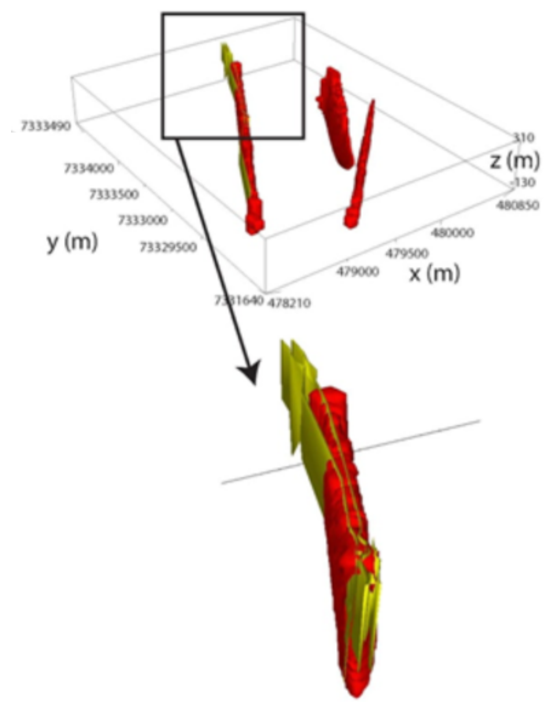
Takeaways



- Early time data:
  - constrain near surface structure infrastructure
  - Improved inversion for late time
- Warm start of inversion was necessary for deep conductors

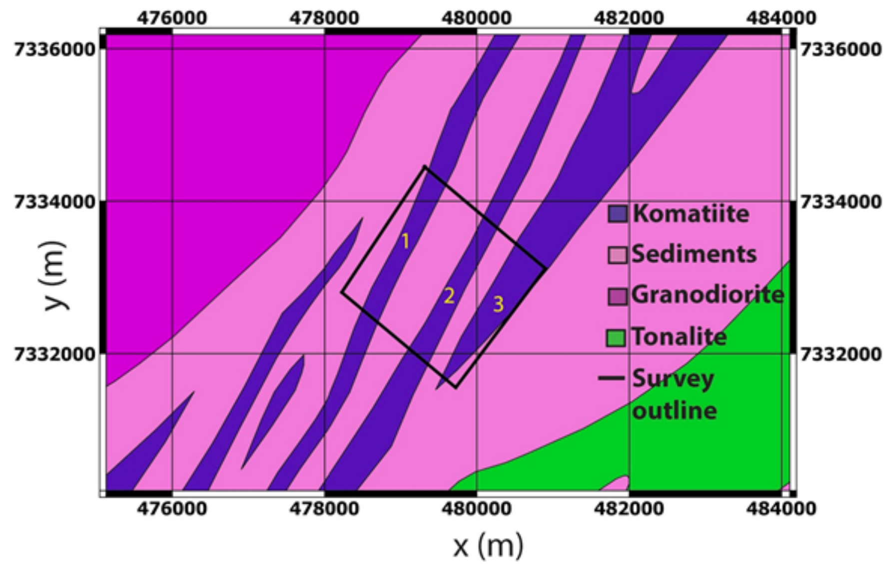
Case History:
VTEM survey over the West Plains orogenic gold region

McMillan et al, 2014



Setup

Geology map

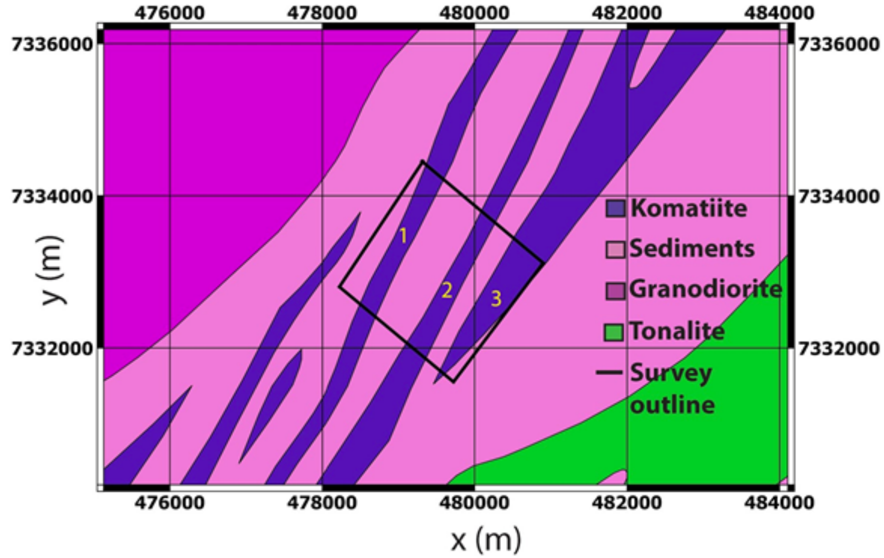


- Ultramafic komatiite units
  - steeply dipping
  - gold mineralization
- Area covered by thin layer of glacial material (outcrops scarce)
- Geology map from regional mag. survey
  - Low resolution; No dip information about the komatiite units

How do we image thin, dipping conductors in 3D?

Properties

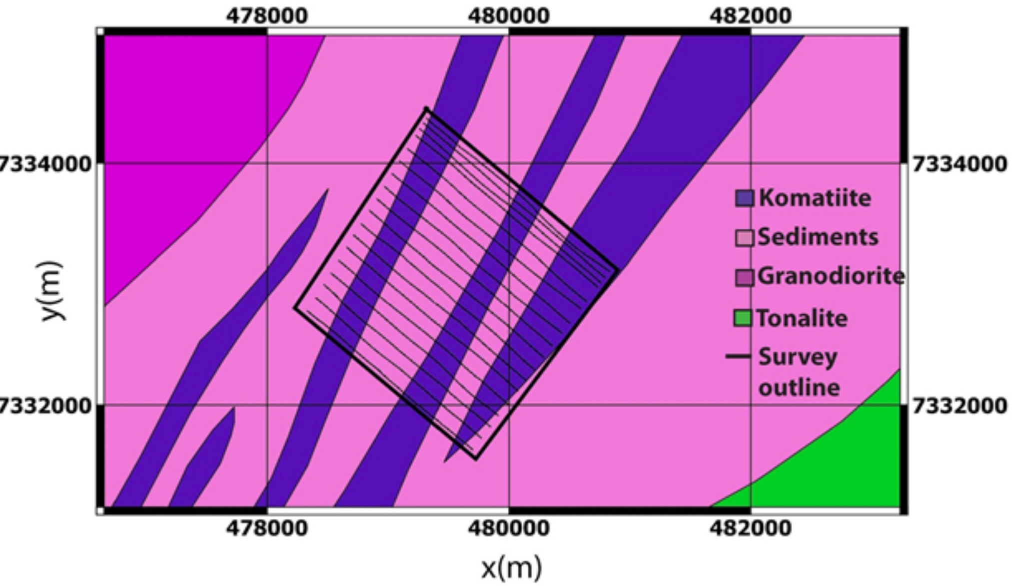
Geology map



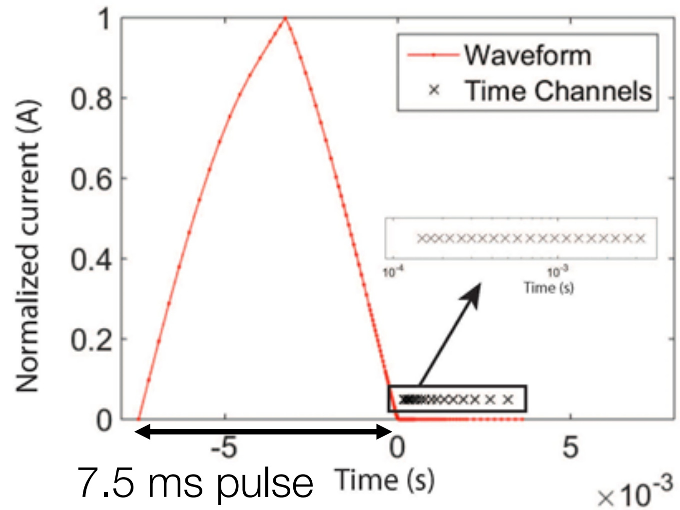
Units	Conductivity	Susceptibility
Komatiite	High	Moderate
Sediments	Moderate	Low
Granodiorite	Low	Low-Moderate
Tonalite	Low	Low-Moderate

Survey: VTEM

Survey lines



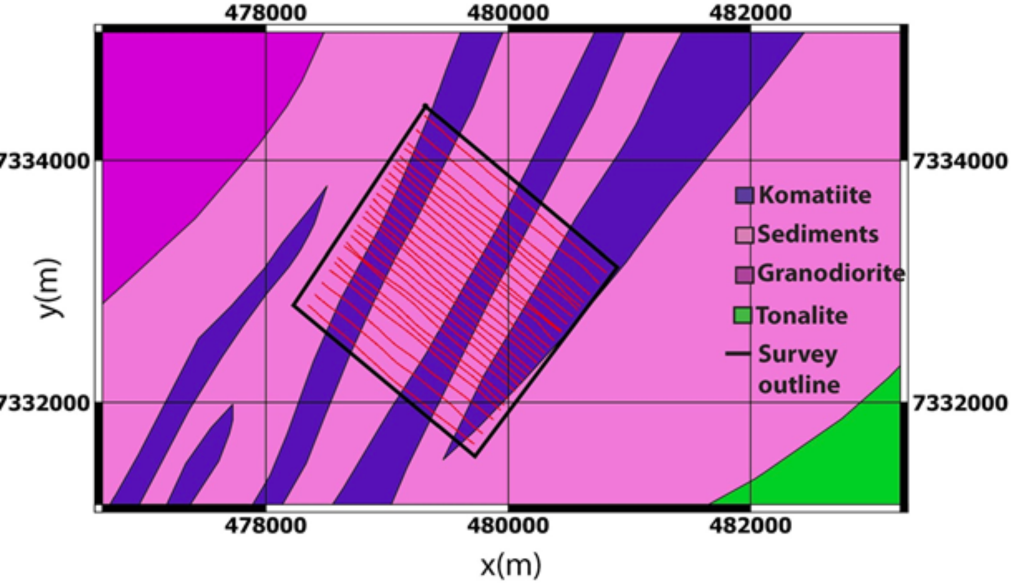
Current waveform



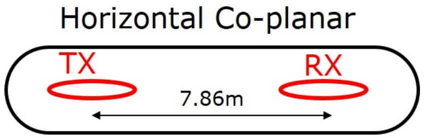
- VTEM (2003) system
  - Line spacing: 120 m; except several lines in the North part (60 m)
  - Line direction: 310 degree
  - Transmitter diameter: 18.5 m
  - Measured component: dBz/dt (26 time channels from 110-6340 μs)

Survey: RESOLVE

Survey lines



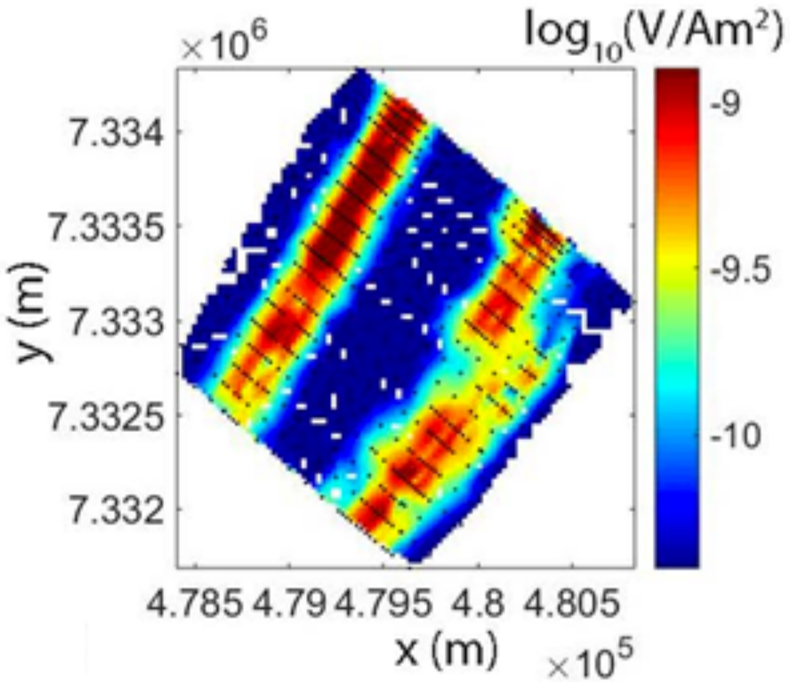
System



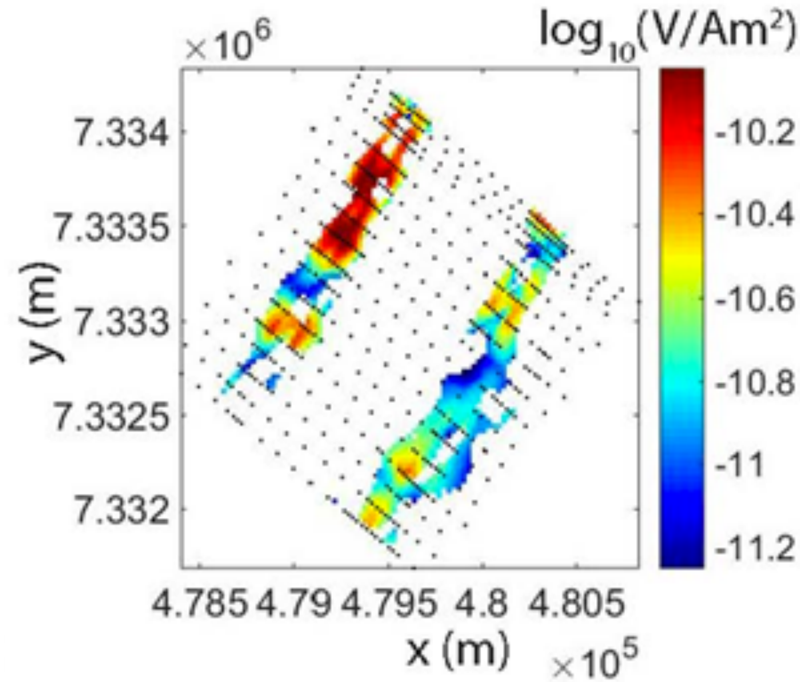
- RESOLVE (2005) system
  - Line spacing: 60 m
  - Line direction: 310 degree
  - Co-planar: 385-115,000 Hz (5 frequencies)

Data: VTEM

dBz/dt at 150 μs



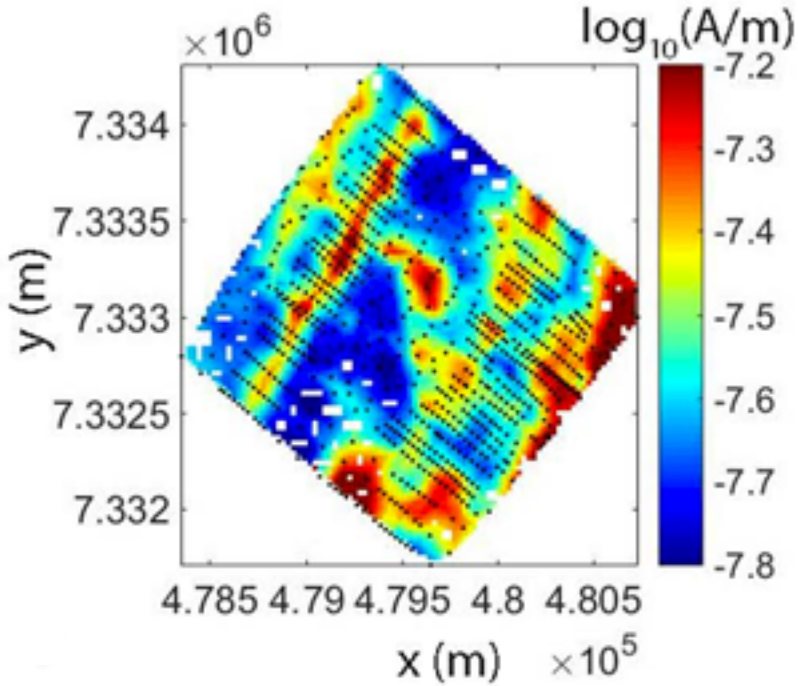
dBz/dt at 3180 μs



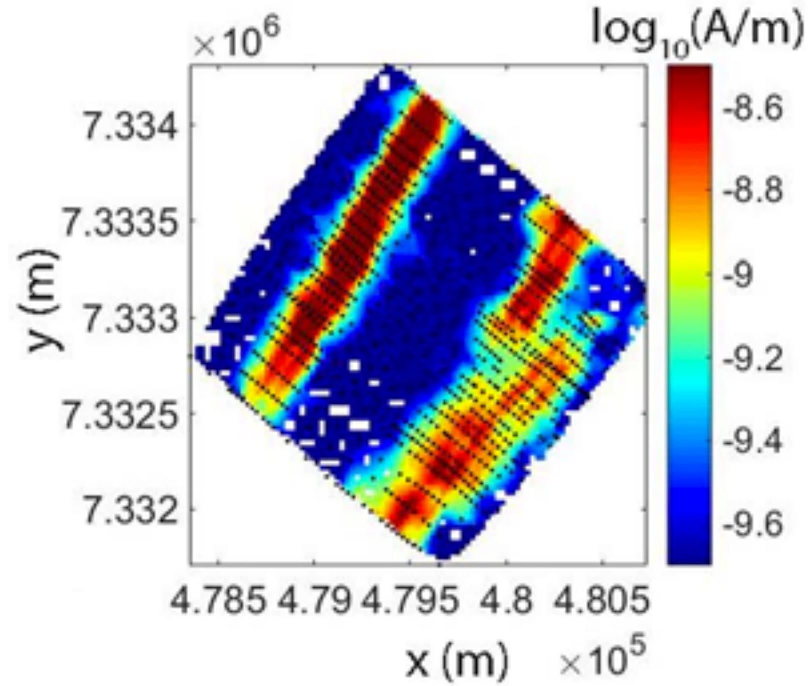
- At 150 μs: strong conductivity anomalies
- Noise level: 5×10^{-12} V/Am^2 (values below blanked-out)

Data: RESOLVE

Bz Imaginary at 115,000 Hz



Bz Imaginary at 385 Hz

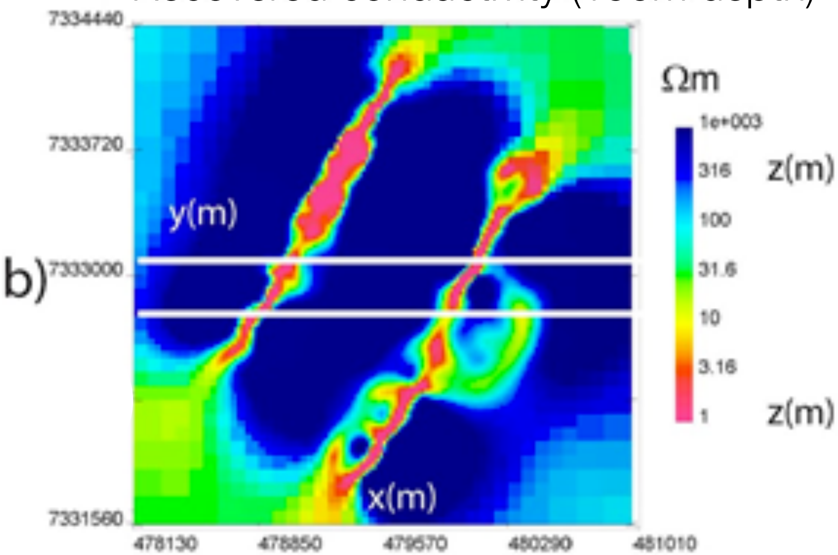


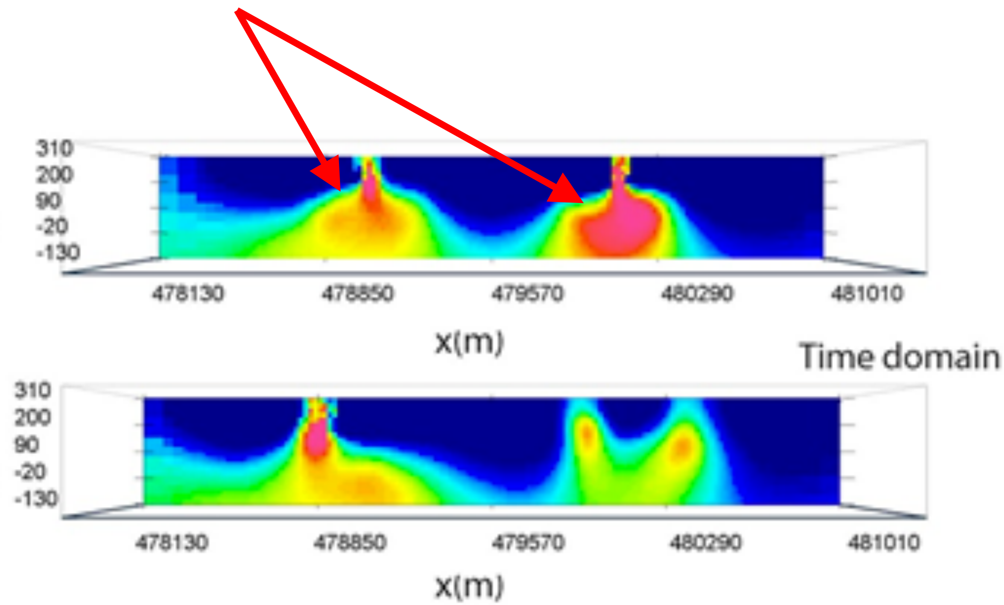
- 115,000 Hz data contains near-surface information
- 385 Hz data similar to the VTEM data at 150 μs

Processing: VTEM

- Voxel inversion
  - Starting model: 1000 Ωm
- Image conductors
- Smooth regularization blurs conductors at depth

Recovered conductivity (190m depth)

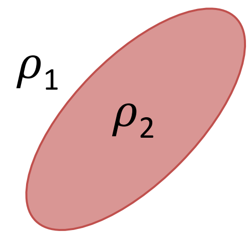




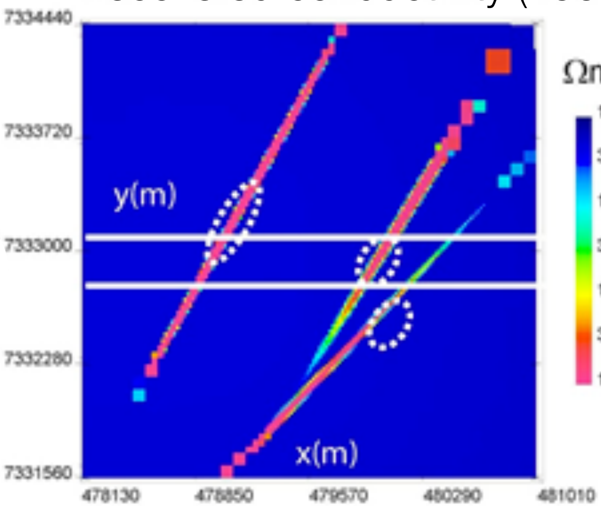
How do we image thin, dipping conductors in 3D?

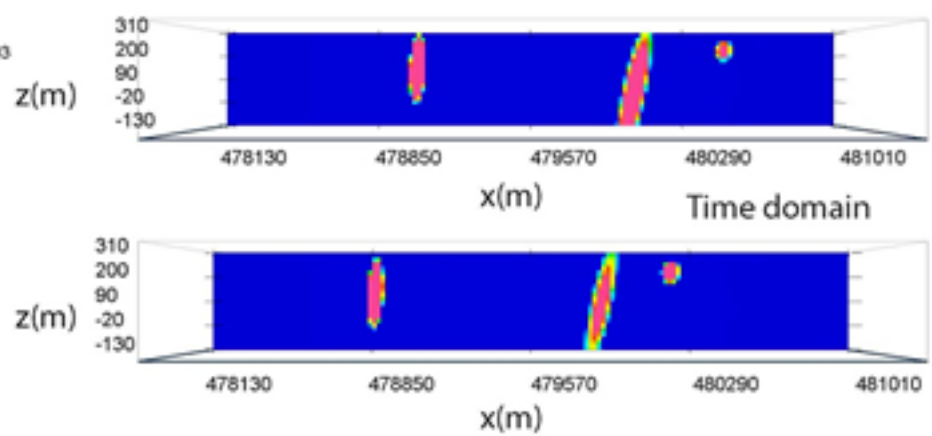
Processing: VTEM

- Parametric inversion
  - Parameterize dipping conductors as Gaussian ellipsoids
  - Invert for:
    - Resistivity: background and ellipsoid
    - Shape and location of ellipsoid



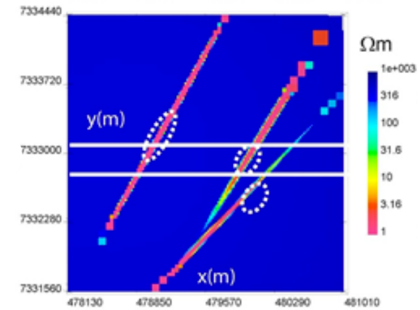
Recovered conductivity (190m depth)



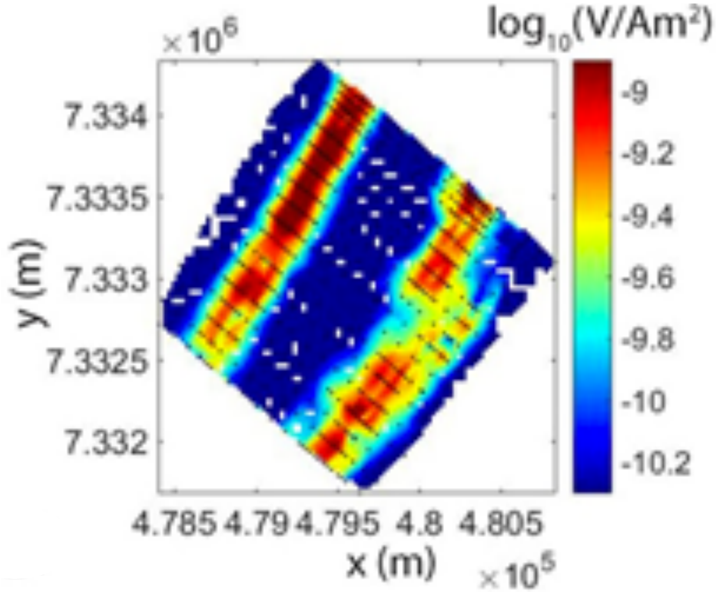


Dashed lines: Initial guess

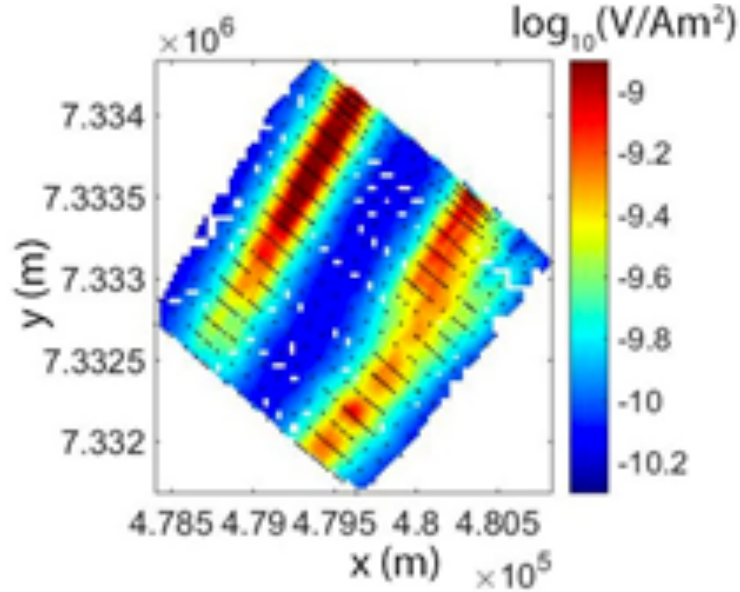
Processing: VTEM



Observed dBz/dt at 150μs



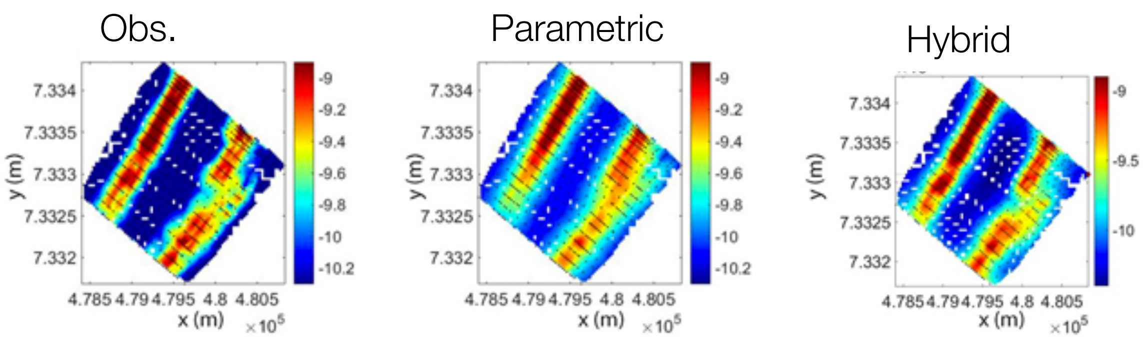
Predicted dBz/dt at 150 μs

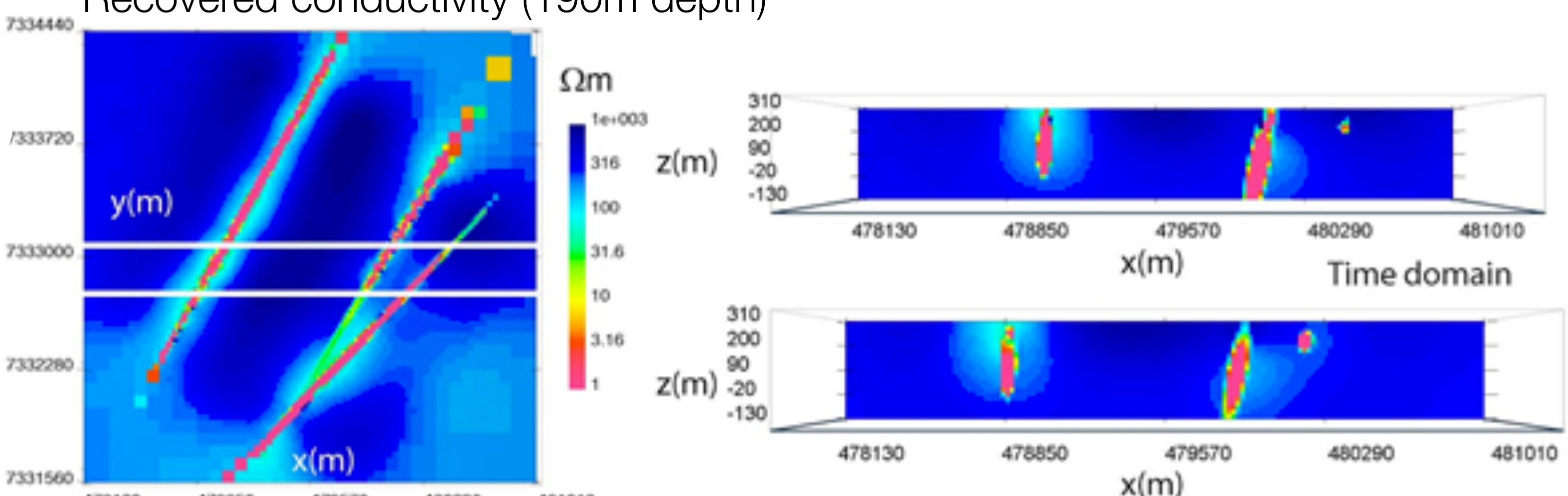


Parametric inversion too simple to explain heterogeneous earth

Processing: Hybrid Inversion

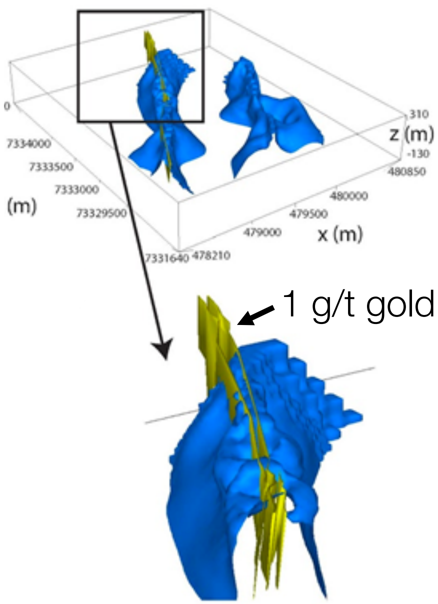
- Voxel inversion using parametric inversion result as initial and reference model



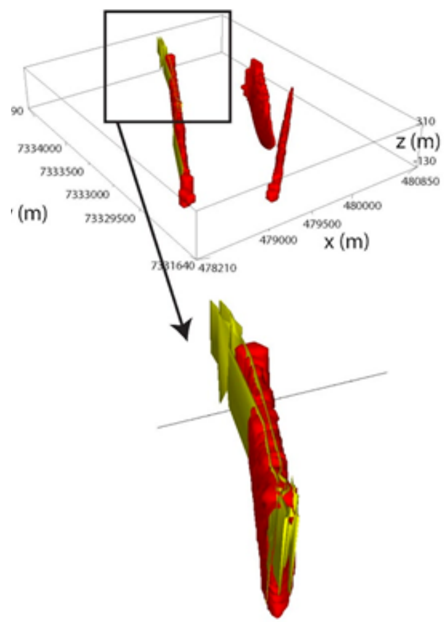


Interpretation: VTEM

Voxel inversion cut-off (30 Ωm)

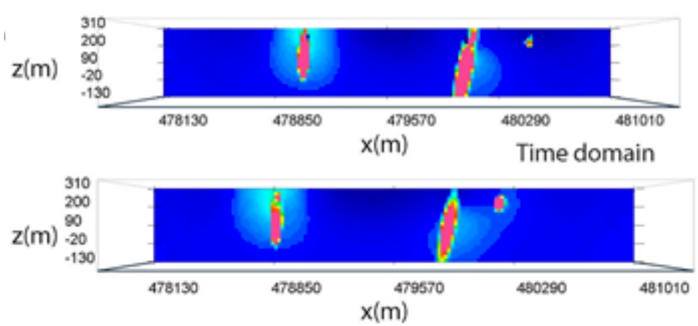


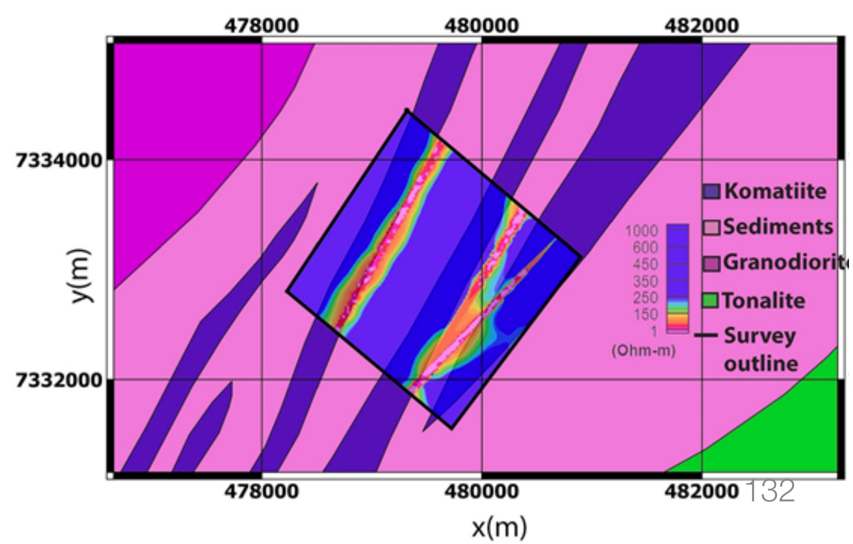
Hybrid inversion cut-off (30 Ωm)



- Voxel inversion: blurs conductors at depth
- Hybrid inversion
  - Dips recovered
  - Tighter boundary of the komatiite
  - Good agreement with gold grade

Hybrid inversion: vertical sections

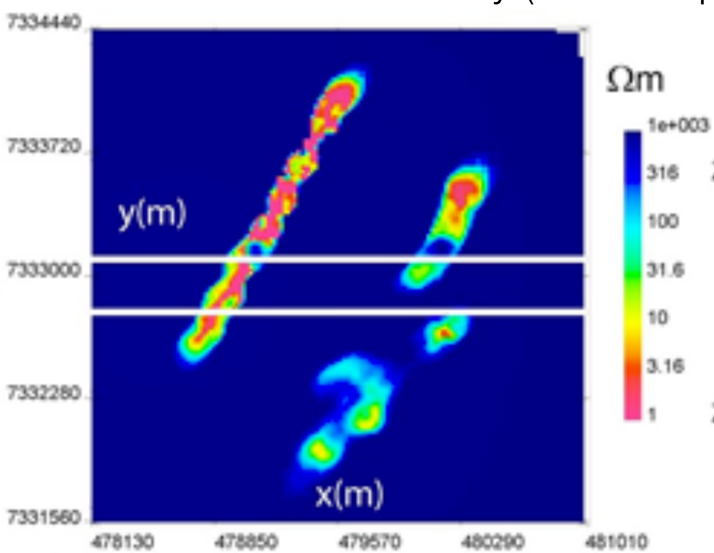


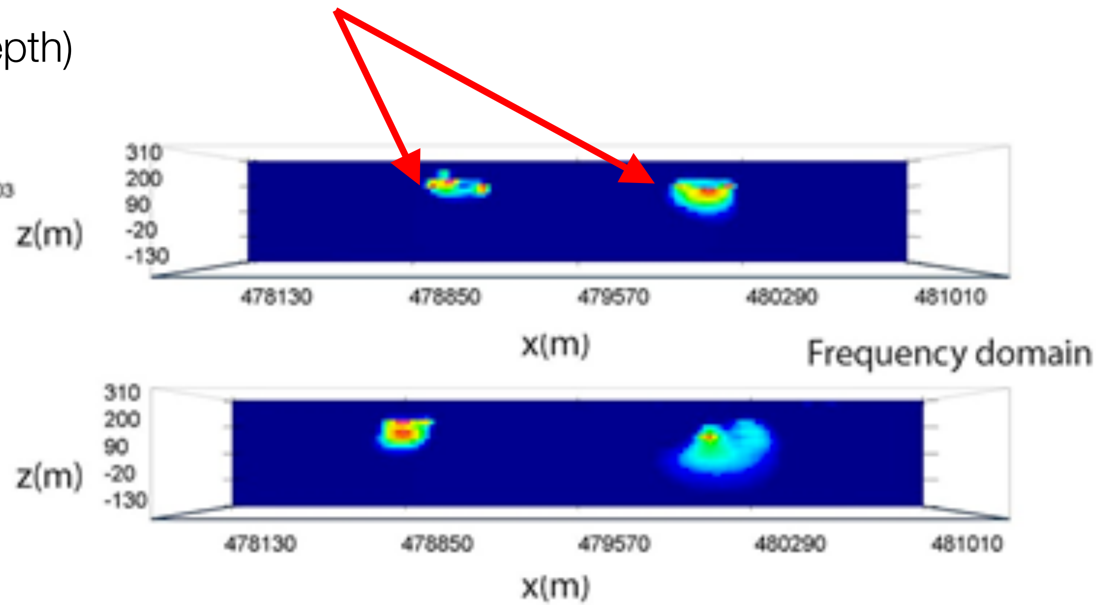


Processing: RESOLVE

- Voxel inversion
  - Starting model: 1000 Ωm
- Image conductors
- Smooth regularization blurs thin conductors

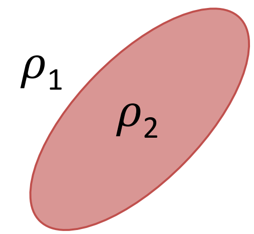
Recovered conductivity (190m depth)



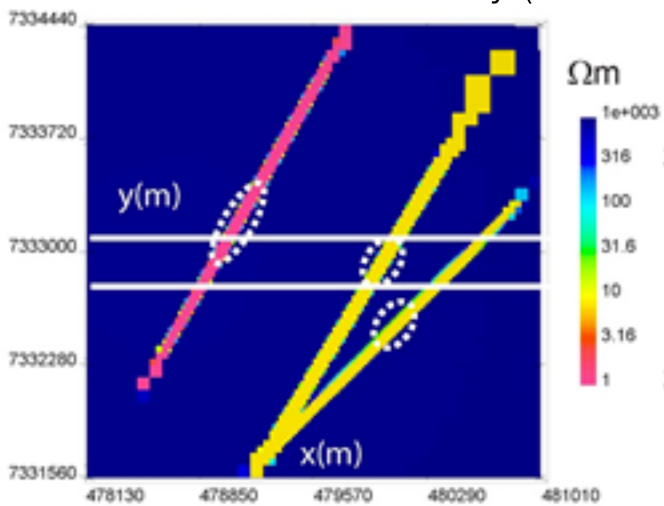


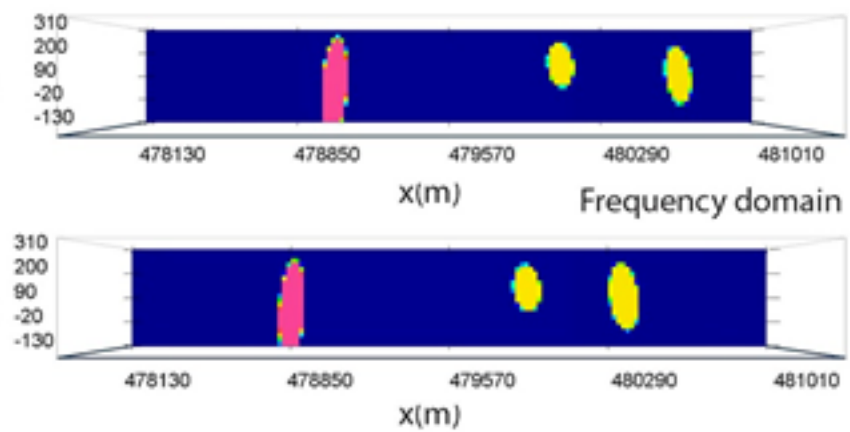
Processing: RESOLVE

- Parametric inversion
  - Parameterize dipping conductors as Gaussian ellipsoids
  - Invert for:
    - Resistivity: background and ellipsoid
    - Shape and location of ellipsoid



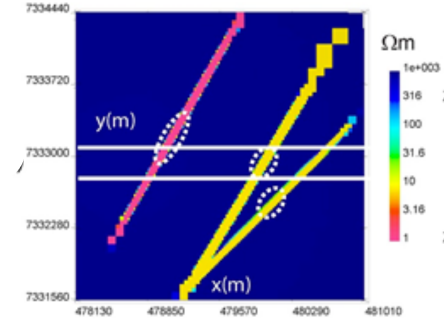
Recovered conductivity (190m depth)



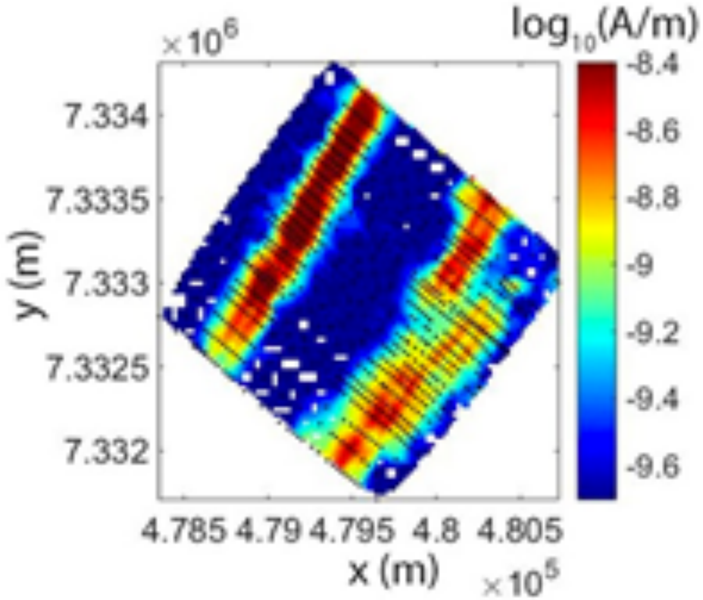


Dashed lines: Initial guess

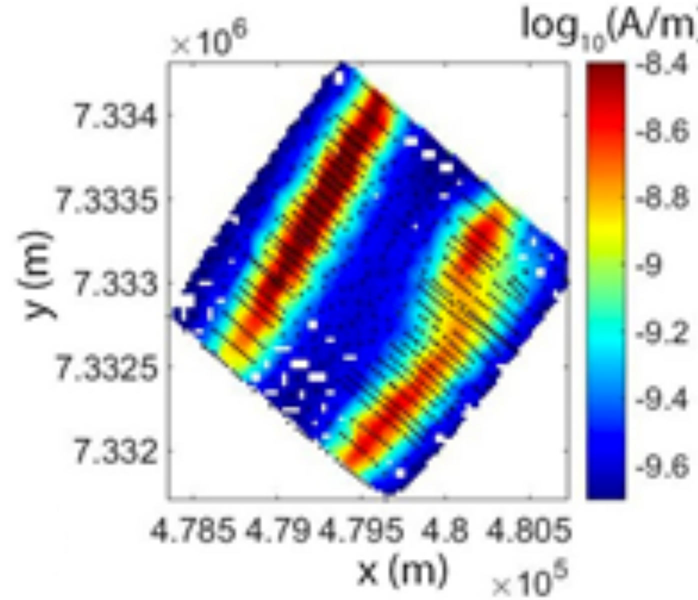
Processing: RESOLVE



Observed Bz Imag at 385 Hz



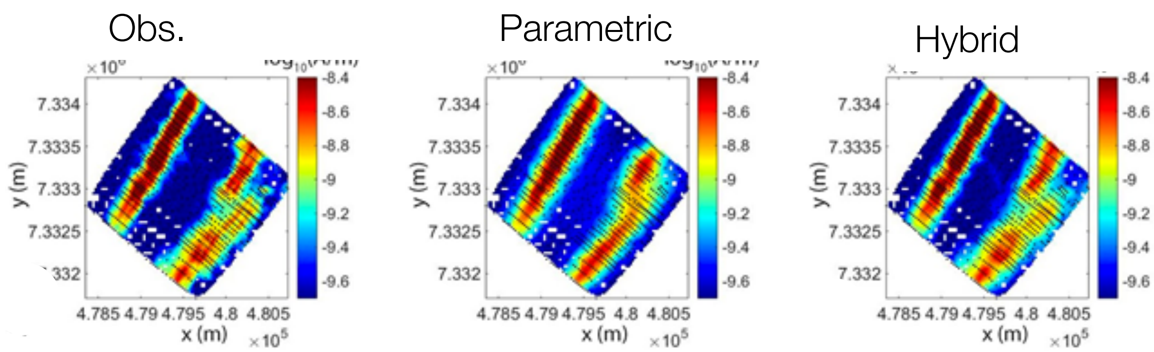
Predicted Bz Imag at 385 Hz

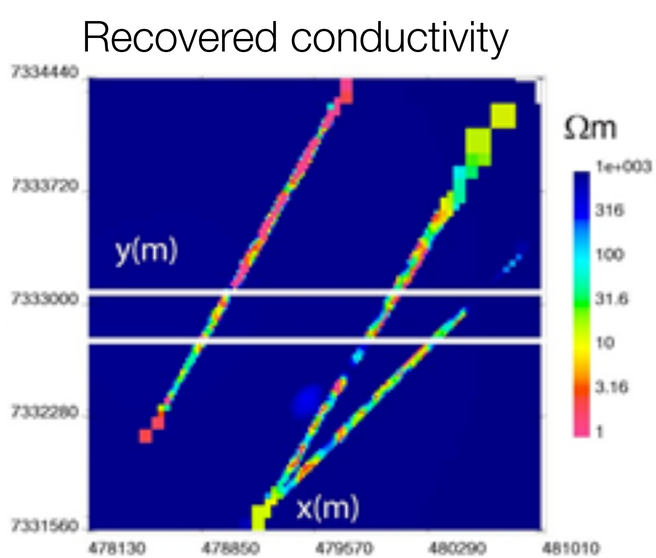


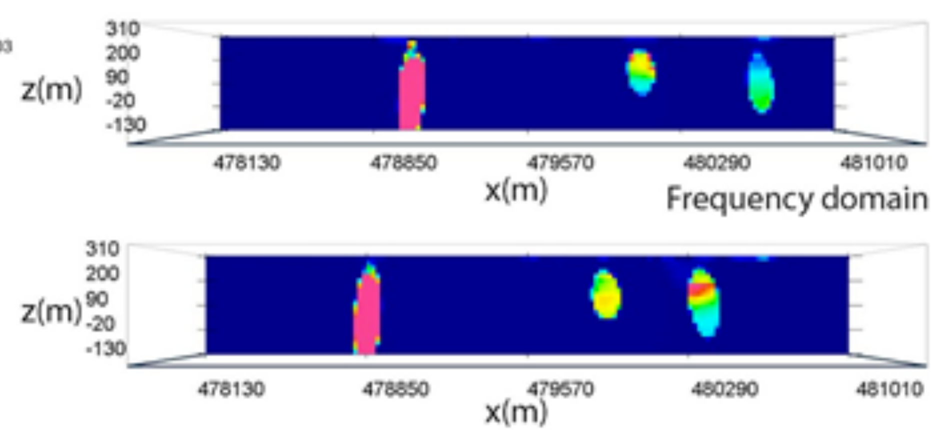
Parametric inversion too simple to explain heterogeneous earth

Processing: Hybrid Inversion

- Voxel inversion using parametric inversion result as initial and reference model

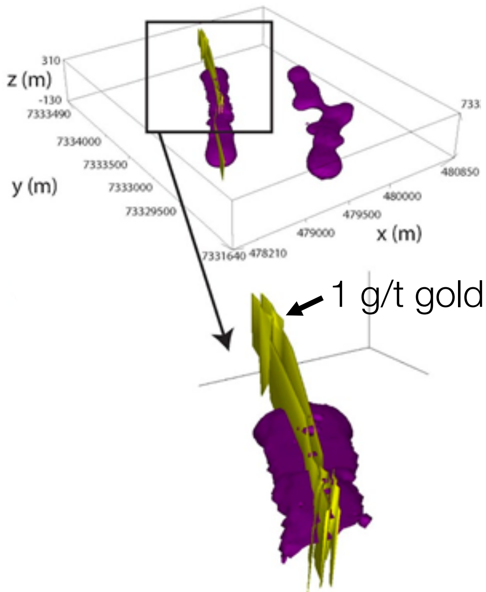




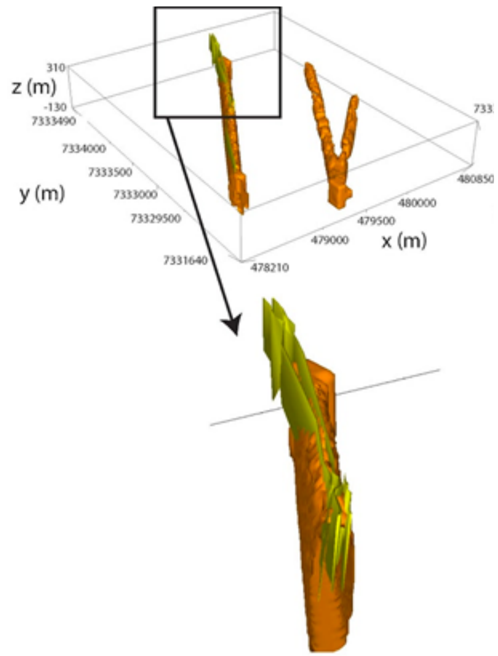


Interpretation: RESOLVE

Voxel inversion cut-off (30 Ωm)

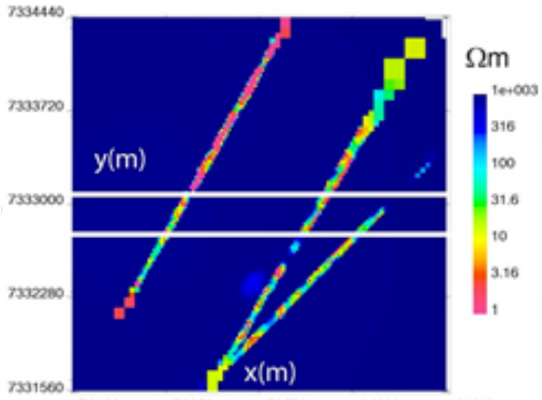


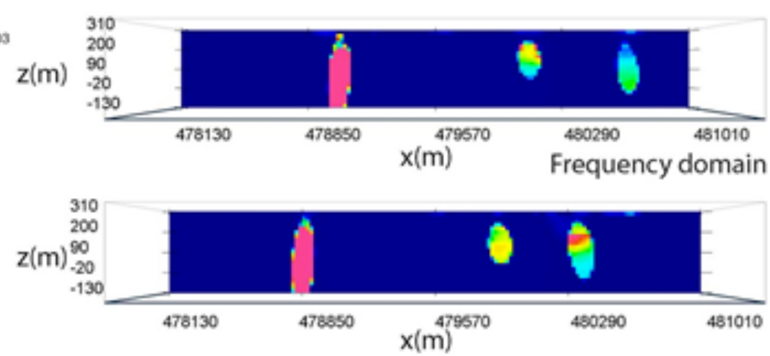
Hybrid inversion cut-off (30 Ωm)



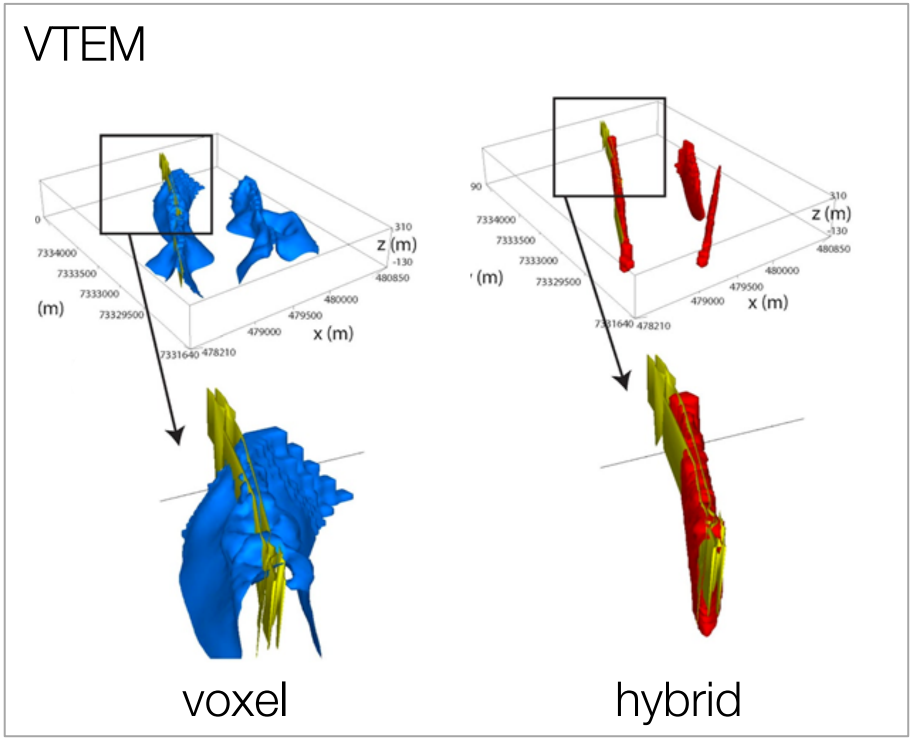
- Voxel inversion: blurs thin conductors
- Hybrid inversion
  - Dips recovered
  - Tighter boundary of the komatiite
  - Good agreement with gold grade

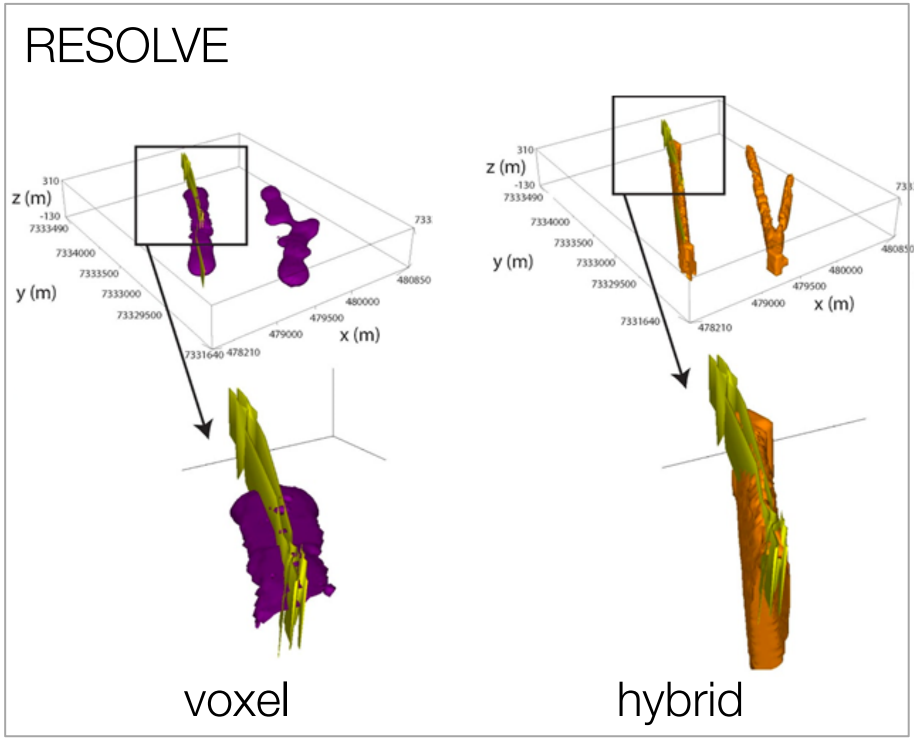
Hybrid inversion





Synthesis





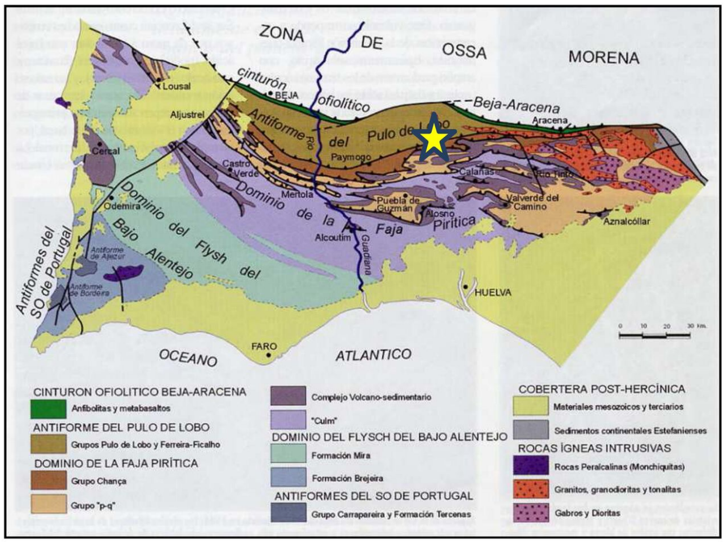
- TDEM and FDEM survey sensitive to conductors
- Hybrid inversion beneficial for imaging thin, dipping conductors

Case History: La Magdalena

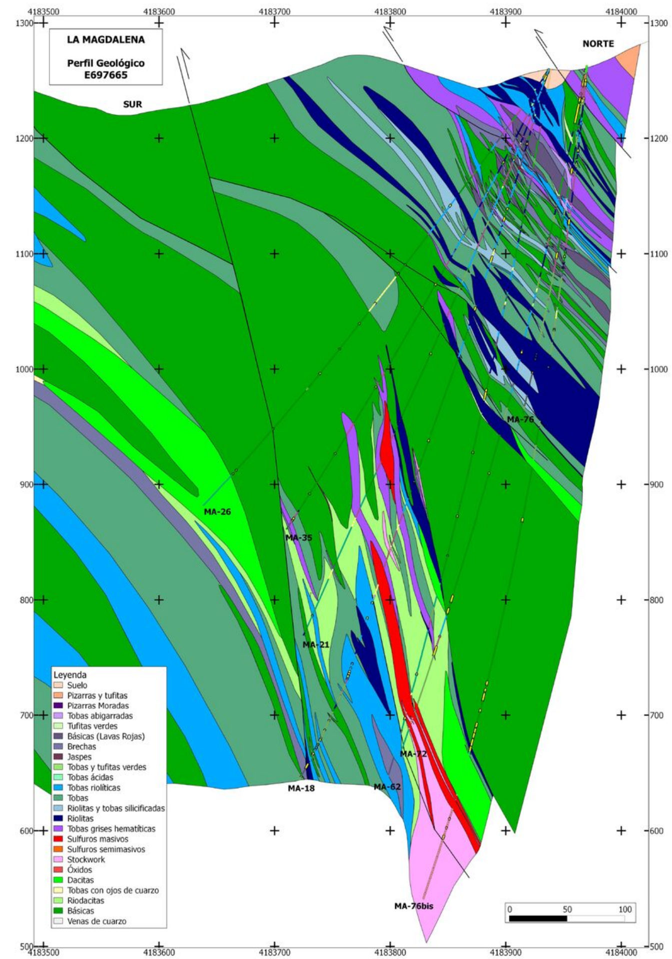
Granda et al., 2016

Setup

Geological setting



Typical cross section



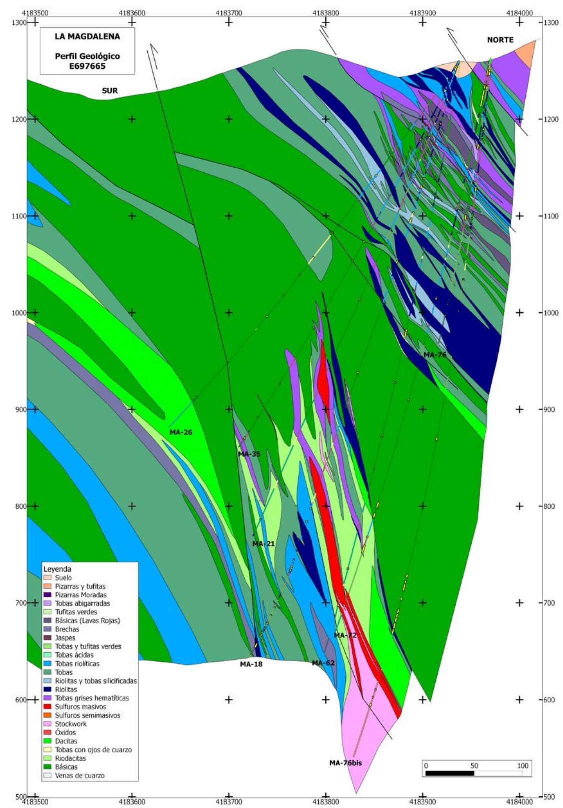
- Volcano-Sedimentary (VS) mineralization
- Thin, steeply dipping veins

Goal: Find deposits

- Use borehole TDEM to find deeper, off-hole targets

Properties

Rock type	Resistivity	Density	Mag sus
Sulfide bodies	Low (<10 Ωm)	High (> 4g/cc)	Low
Host Rock (VS)	High		Low

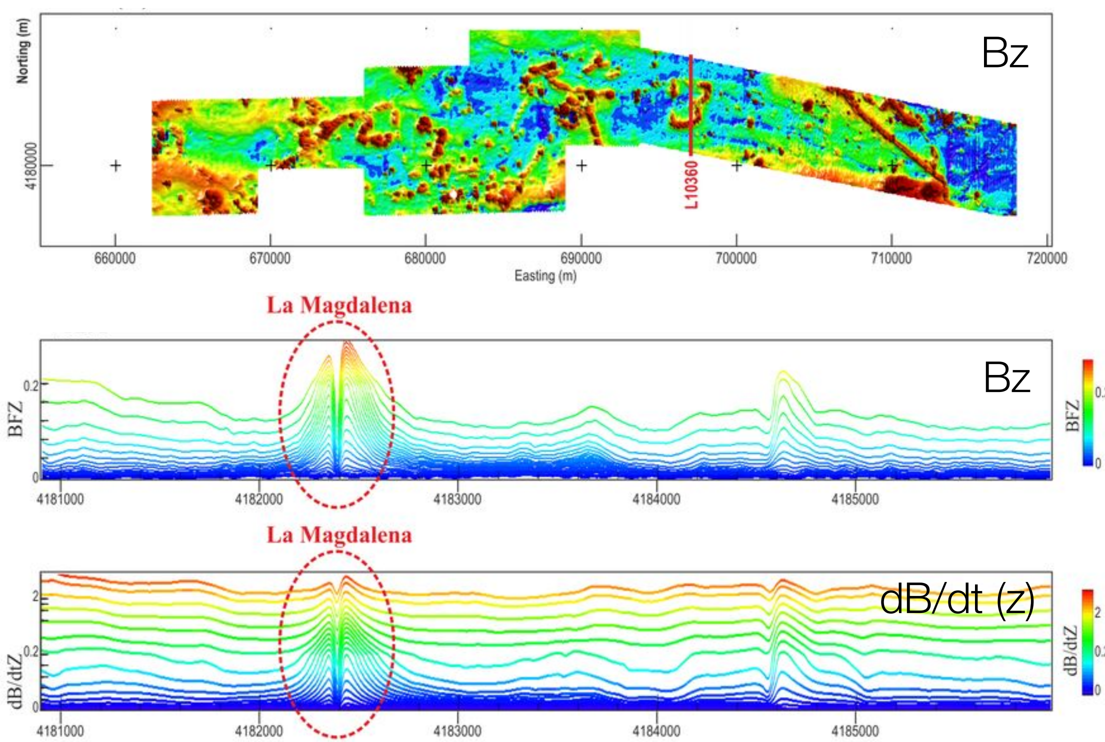


Surveys: Strategic Campaigns

Goal	Survey	Detail
Find potential targets	VTEM	350 km^2
Evaluate continuity of mineralization	Mise-a-la-Masse	Single current in ore body
Methodological Tests	ERT	Pole-dipole along a single line
	Surface TEM: Turam configuration	
	Surface TEM: Slingram configuration	
Find off-hole conductors	Borehole TDEM	Surface transmitter Borehole receivers

Initial Discovery: VTEM

- VTEM airborne survey
  - 350 km^2 area
  - N-S lines,100m - 200m spacing
  - Measure:
    - dB/dt (x, z)
    - Bz, Bx
    - Mag.

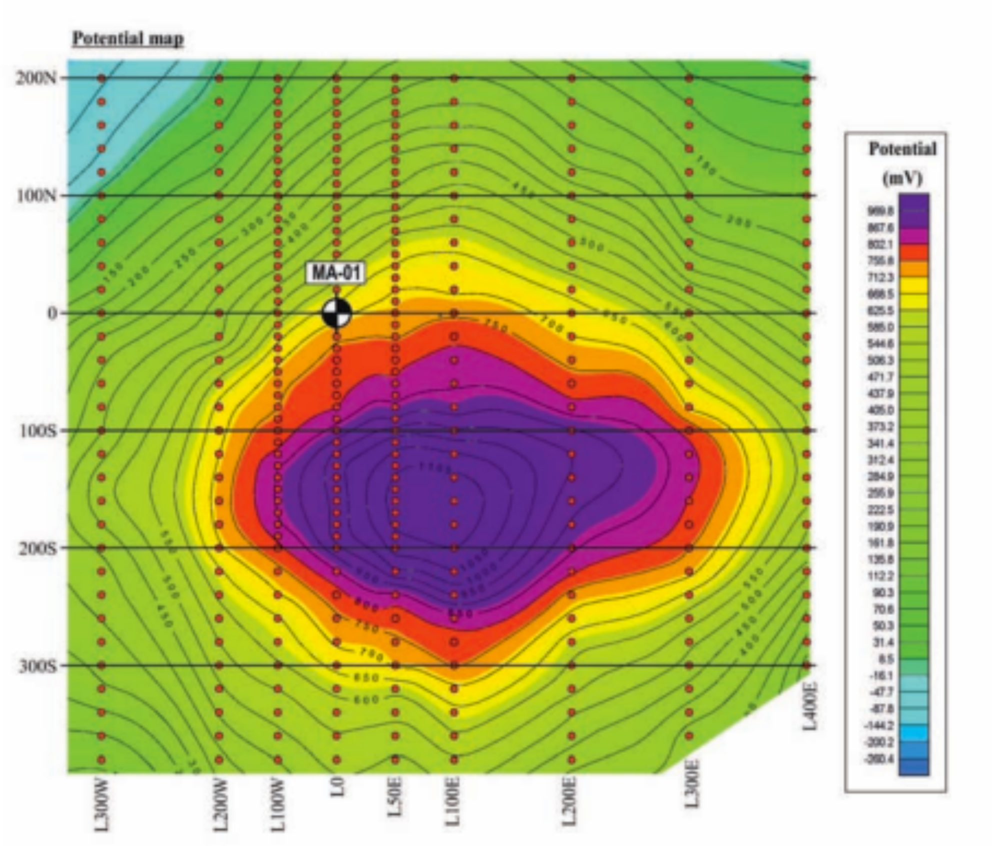


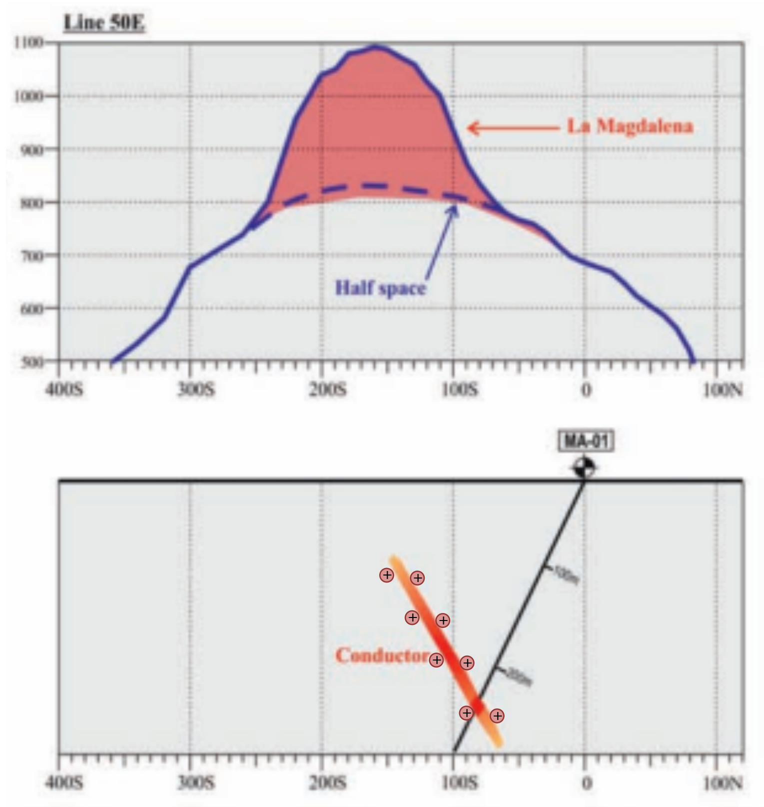
Survey Parameters

Sensor height	50 m
TX radius	17.5 m
Current Peak in TX	234 A
Magnetic Moment in TX	900.437 nIA
Z oriented RX radius	0.6m
Z oriented RX # turns	100
X oriented RX radius	0.16m
X oriented RX # turns	245

Evaluation: Mise-a-la-masse

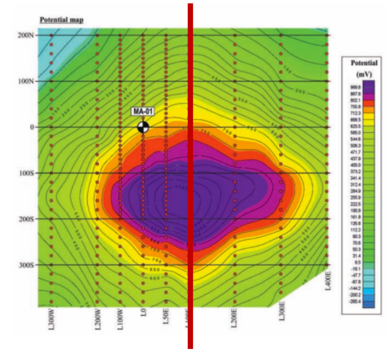
- Electrode coupled to massive sulphides at 230m
- Measure potentials (gradient mode) on surface

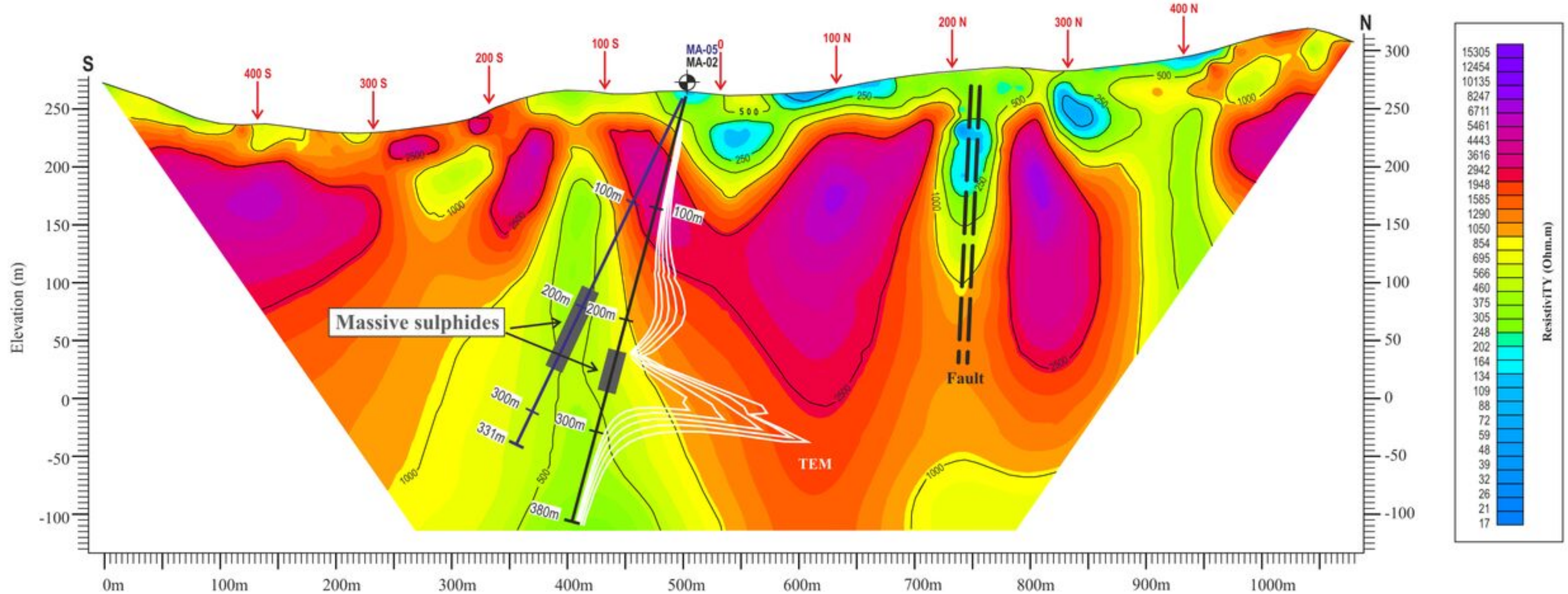




Methodological Test: ERT

- Pole-dipole
  - a = 20m and n = 40

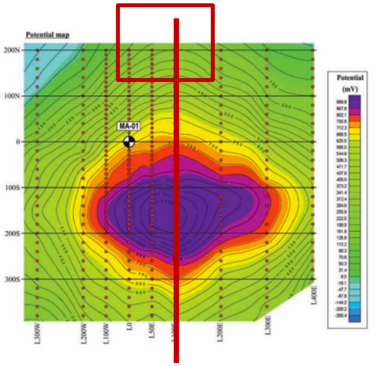




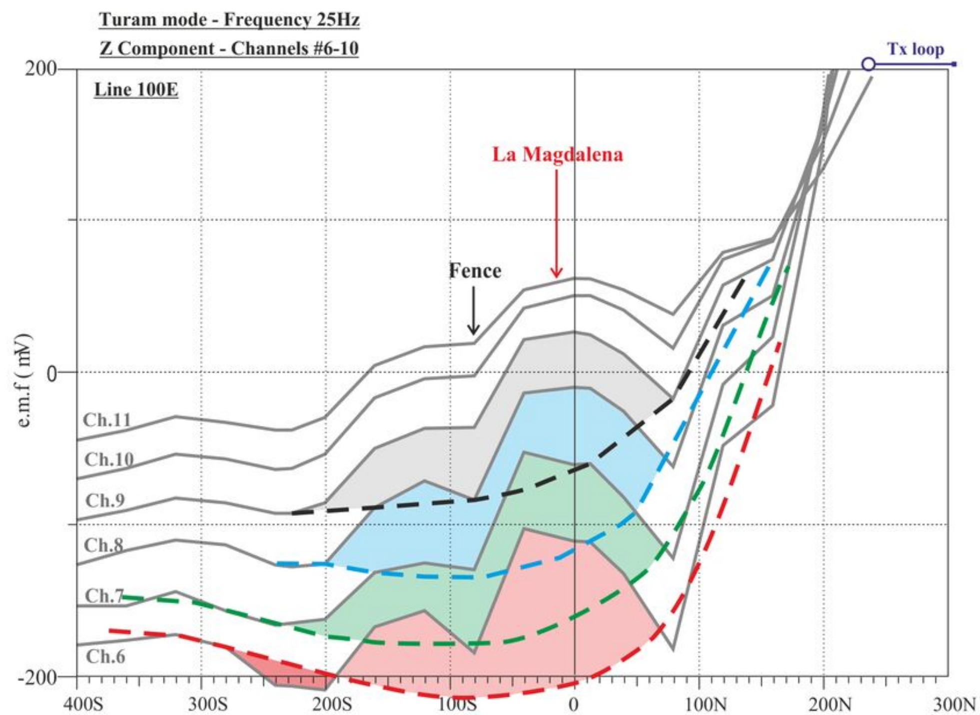
Results: found a moderately low resistivity region, not as low as anticipated

Methodological Test: Turam

- Ground based, fixed loop: Turam
- PROTEM induction coil
  - RX Equivalent area: 100 m^2
- TX located several hundred meters north of mineralization
  - (ensure good EM coupling)



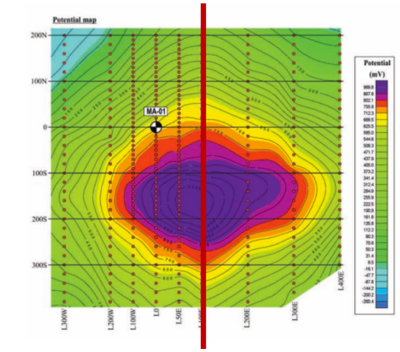
Specification	Turam
TX Loop size	700 m x 400 m
TX-RX synchronization	Crystal
Current pulses	15.5 A
T/O time	295 µs
Measured parameters	dBdt (z, x)
Base frequency	Hi: 25 Hz MD: 6.25 Hz
Measurement mode	Off time

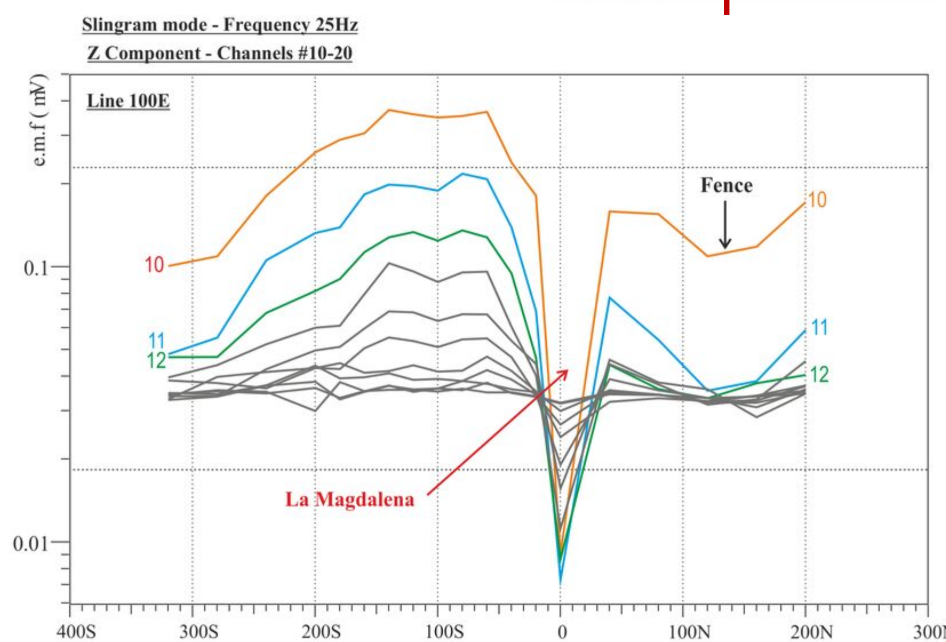


Results: Strong detectability.

Methodological Test: Slingram

- Ground based, moving loop: Slingram
- PROTEM induction coil
  - RX Equivalent area: 100 m²





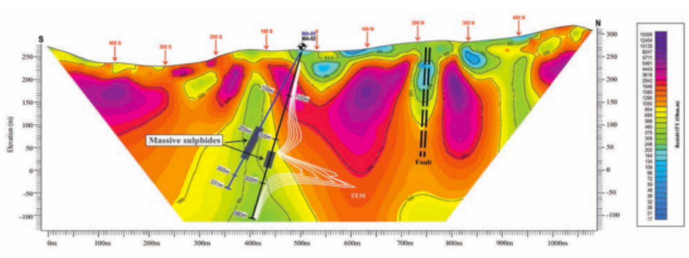
Specification	Turam	Slingram
TX Loop size	700 m x 400 m	100 m x 100 m
TX-RX synchronization	Crystal	Ref. Cable
Current pulses	15.5 A	22 A
T/O time	295 µs	75 µs
Measured parameters	dBdt (z, x)	dBdt (z, x)
Base frequency	Hi: 25 Hz MD: 6.25 Hz	Hi: 25 Hz MD: 6.25 Hz
Measurement mode	Off time	Off time

Characteristic plate-like conductor.
Dipping north

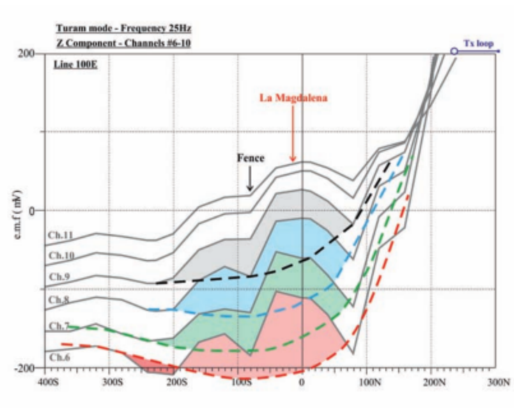
Results: Strong detectability.

Methodological Test: Final choice Turam

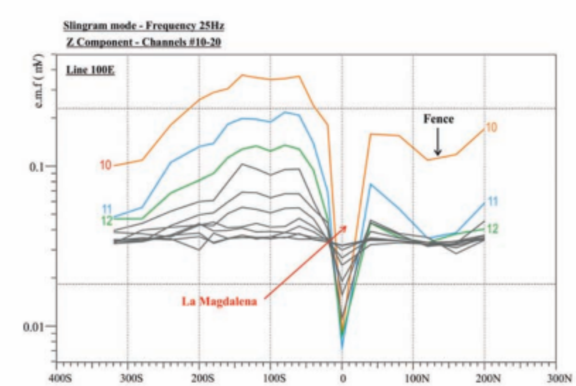
ERT: Inconclusive



Turam: Strong signal

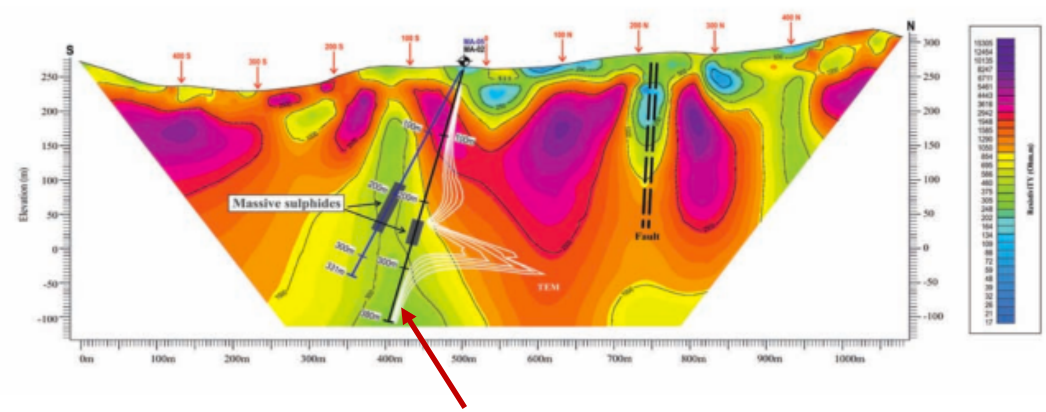


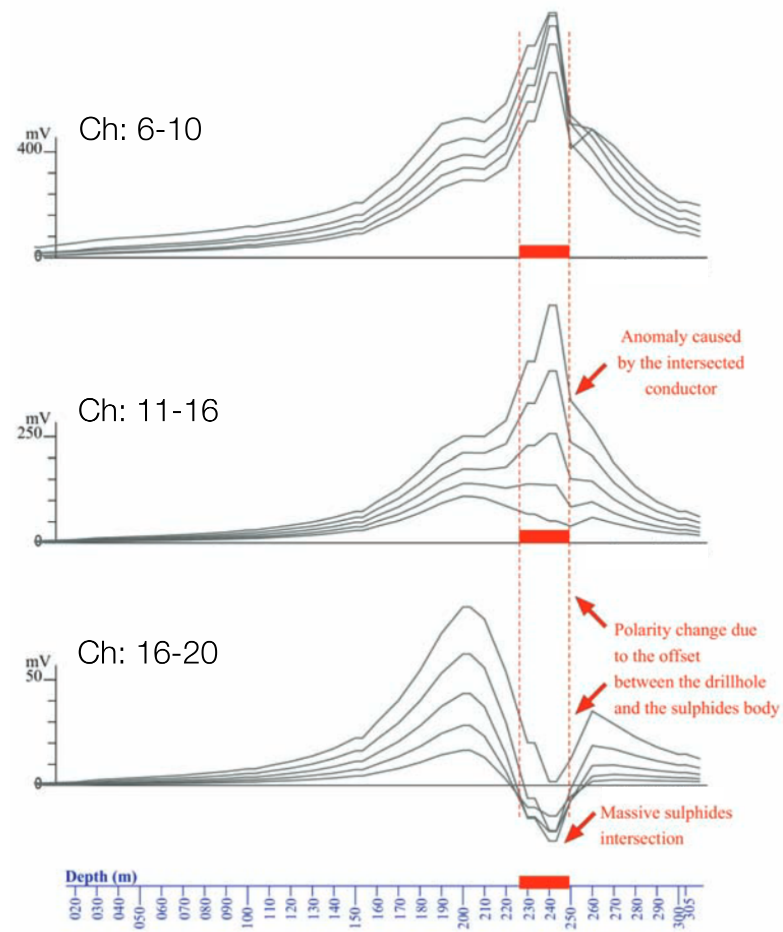
Slingram: Strong signal



Borehole TDEM

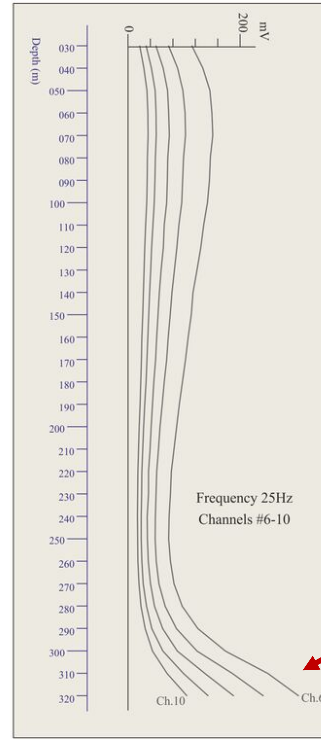
- PROTEM system
  - TEM-67 transmitter
  - BH-43-3D probe (3-components)
  - Base Frequencies: Hi (25 Hz), MD (6.25 Hz)





Borehole TDEM: Discovery of Masa 2

- Borehole TDEM carried out using multiple drillholes
- MA-21 drilled to 320m (Phase 1)
  - Did not intersect mineralization
  - Indicate an off-hole conductor

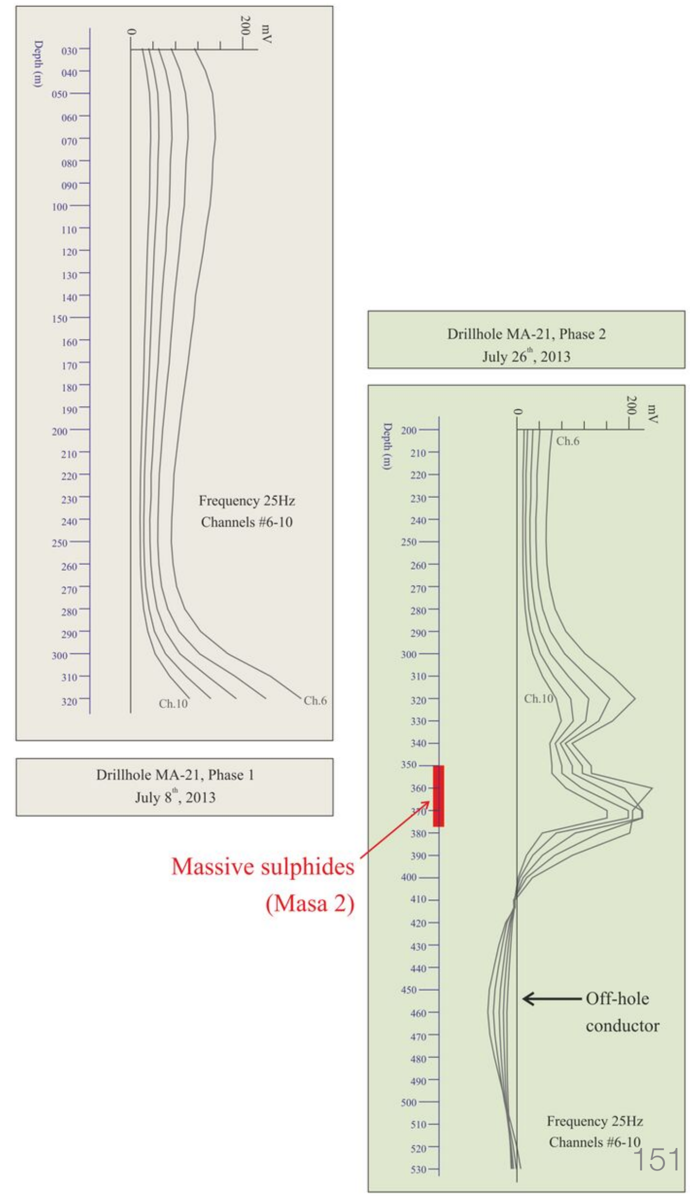


Drillhole MA-21, Phase 1
July 8th, 2013

Possible off-hole conductor

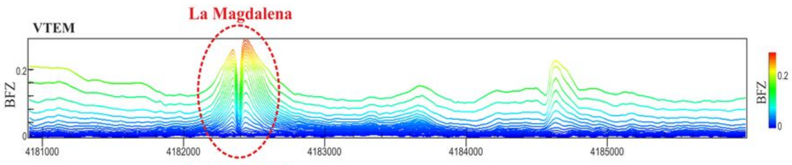
Borehole TDEM: Discovery of Masa 2

- Borehole TDEM carried out using multiple drillholes
- MA-21 drilled to 320m (Phase 1)
  - Did not intersect mineralization
  - Indicate an off-hole conductor
- MA-21 drilled to 520m (Phase 2)
  - Mineralization 350-370m

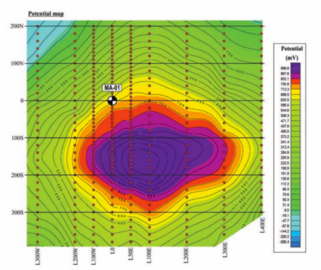


Synthesis

- VTEM: initial discovery

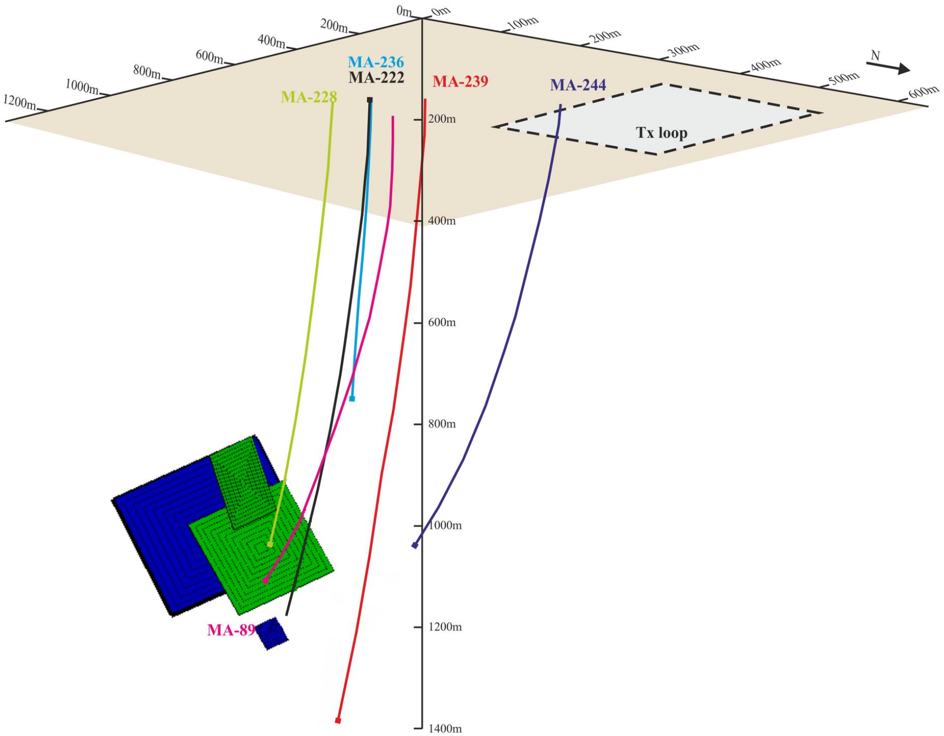


- Mise a la Masse: evaluation



- Ground surveys: methodological tests
  - ERT
  - Turam
  - Slingram

- Borehole TDEM: find off-hole conductors

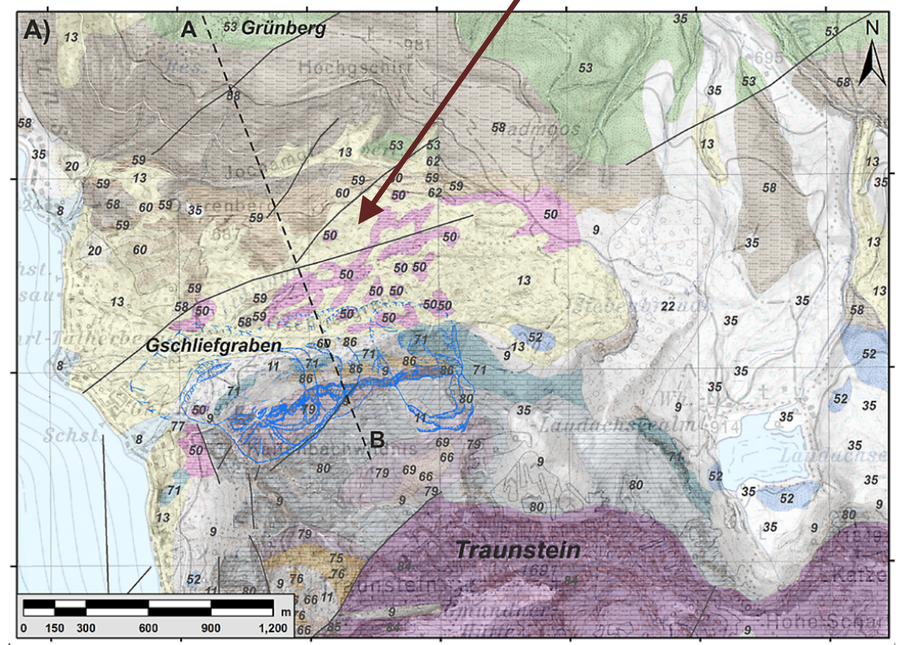


Case History: Airborne geophysical mapping for landslide investigation

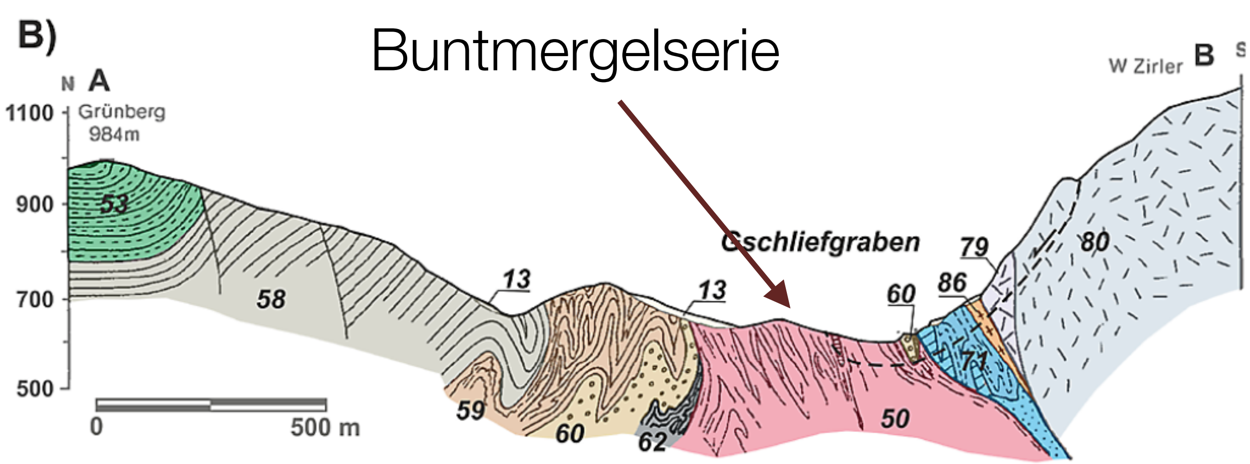
Supper et al., 2013

Setup

- Gschliefgraben area: most prominent recent landslide of Austria
- Clay layers absorb water → become a plane of weakness and result in a landslide
- SafeLand Project: evaluate airborne geophysics

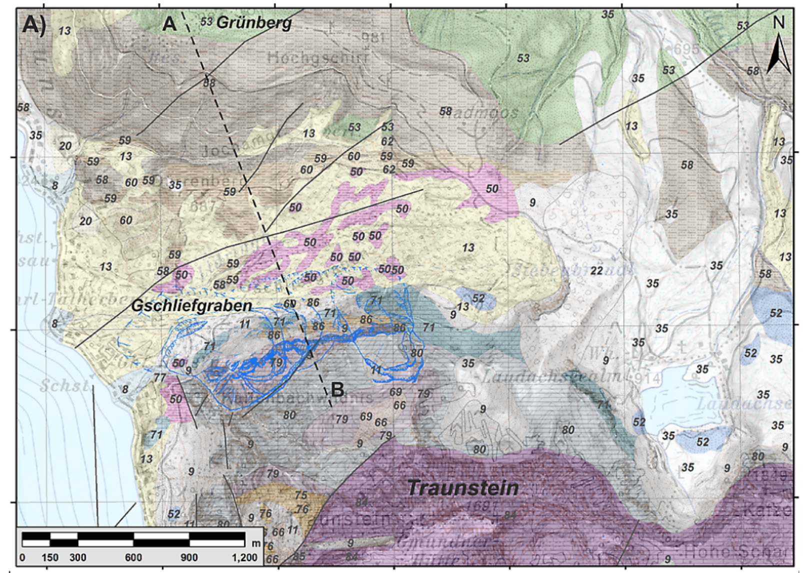


Buntmergelserie

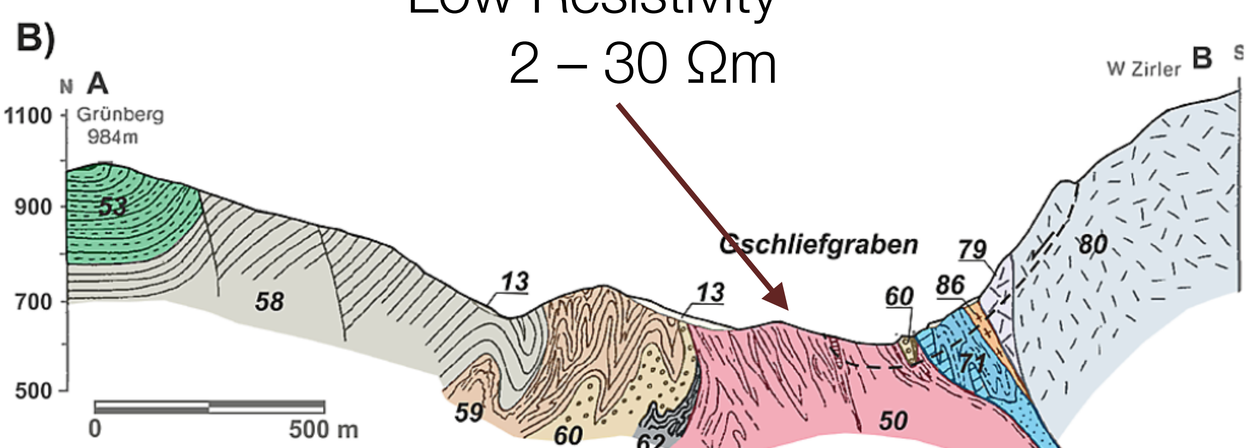


Properties

Deformed variegated marl, claystone, … (target unit)	2 – 30 Ωm
Claystone, marl	50 – 100 Ωm
Intermediate Sandstone	> 150 Ωm

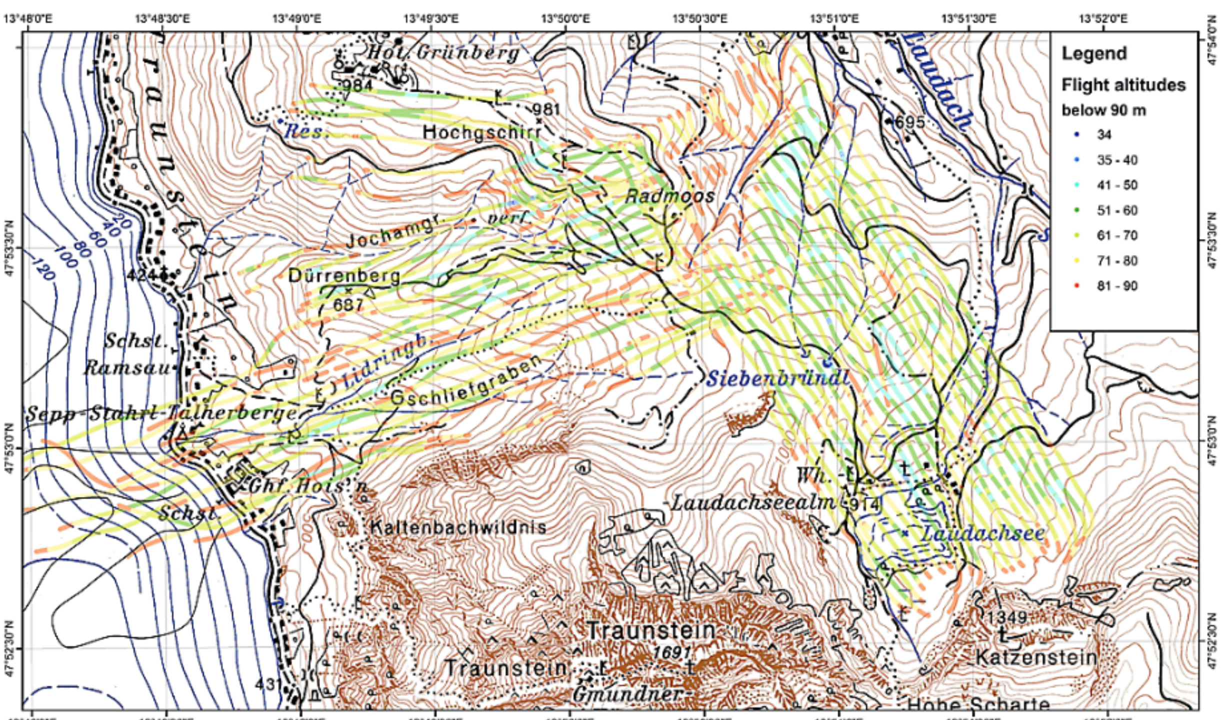


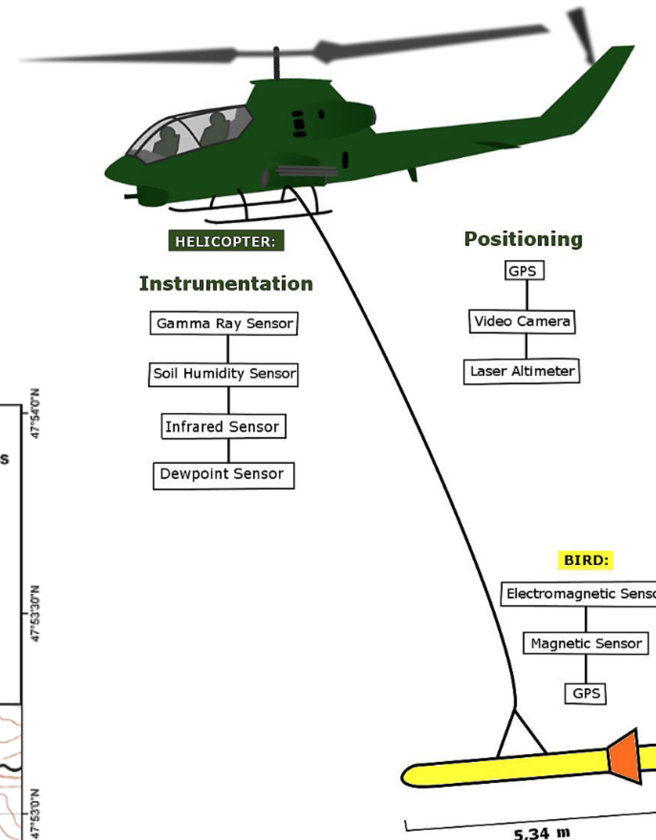
Buntmergelserie
Low Resistivity
2 – 30 Ωm



Survey

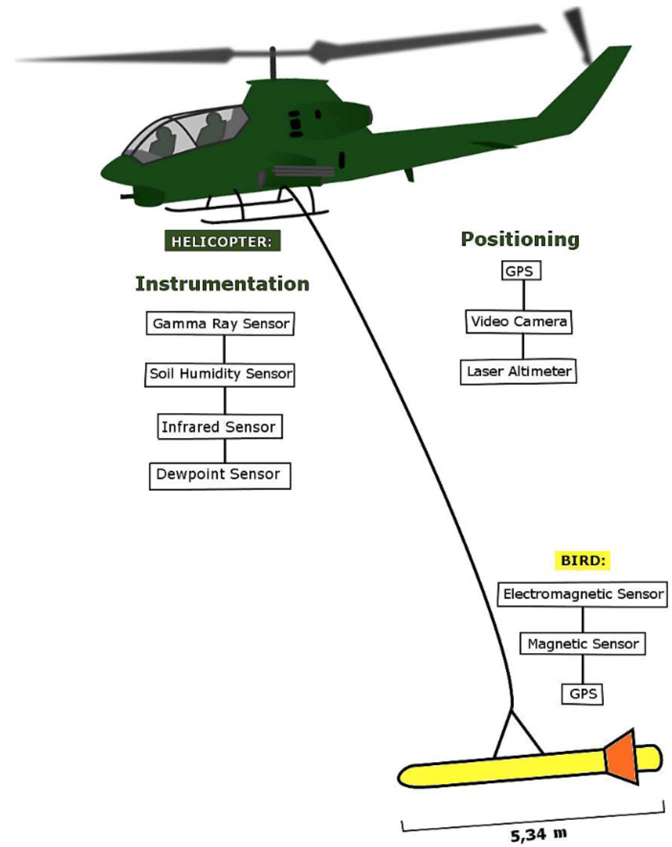
- Multiple airborne sensors
  - **Airborne EM**
  - Gamma Ray
  - Magnetics
  - Passive Microwave

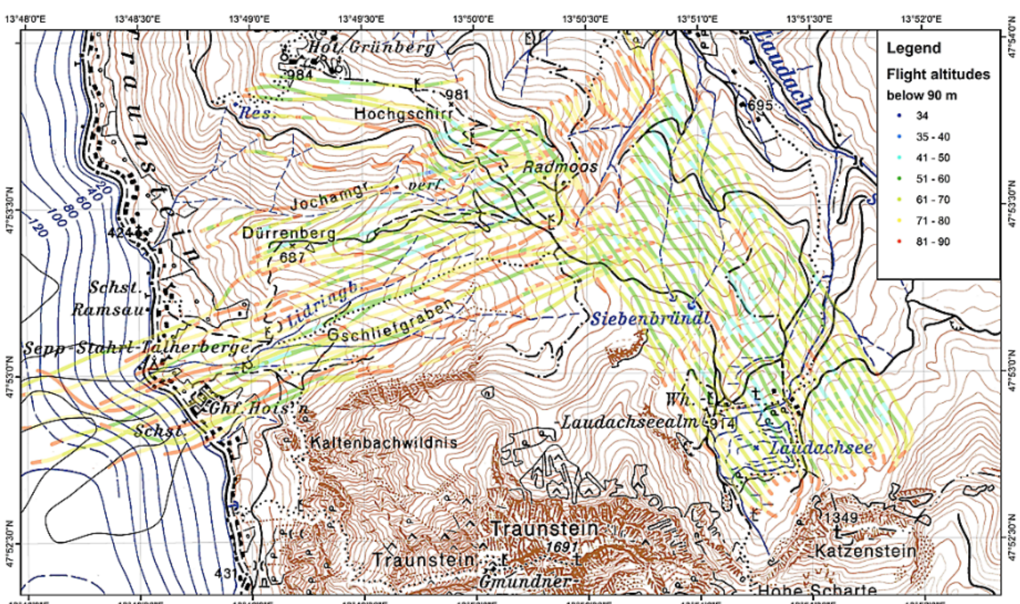




Survey: Airborne EM

- Frequency domain system
  - Frequencies: 340 Hz, 3200 Hz, 7190 Hz and 28 850 Hz
- Sensor height needs to be < 90 m
- Rough topography → flown only uphill (2x flight time)

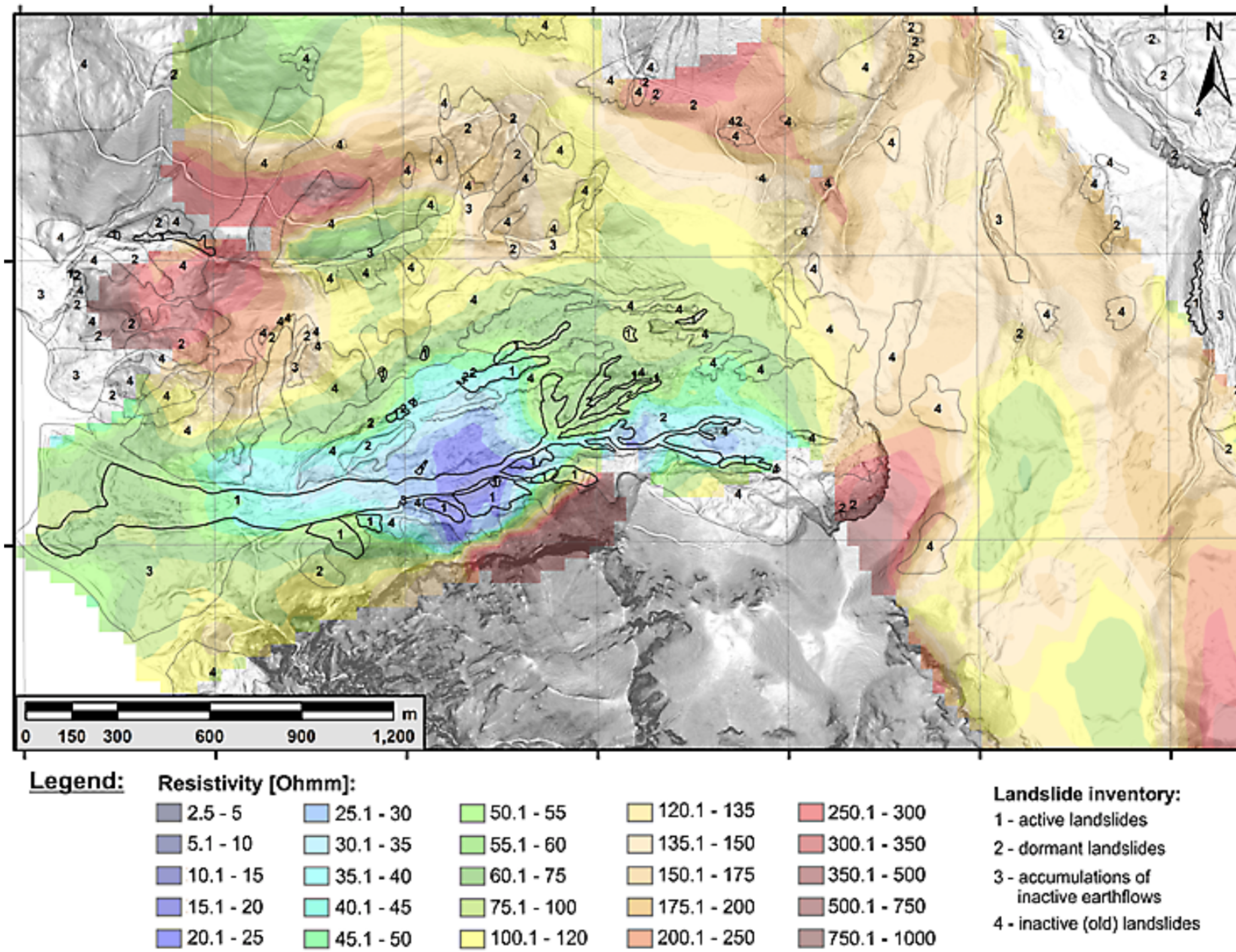




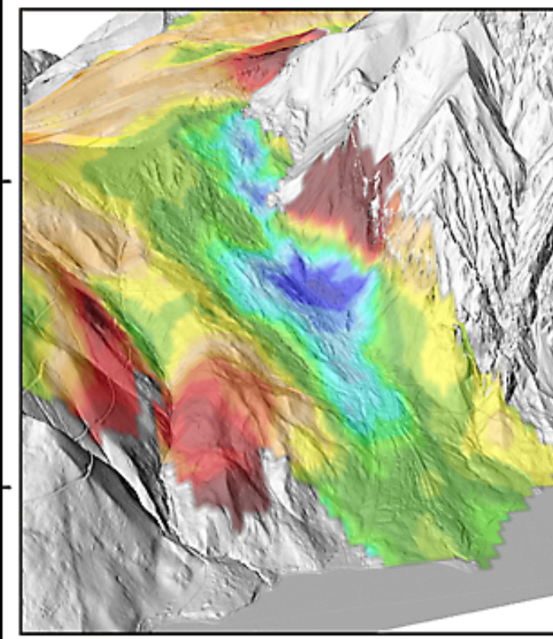
Data & Processing

- Data inverted in 1D

resistivity 0 – 2m below surface



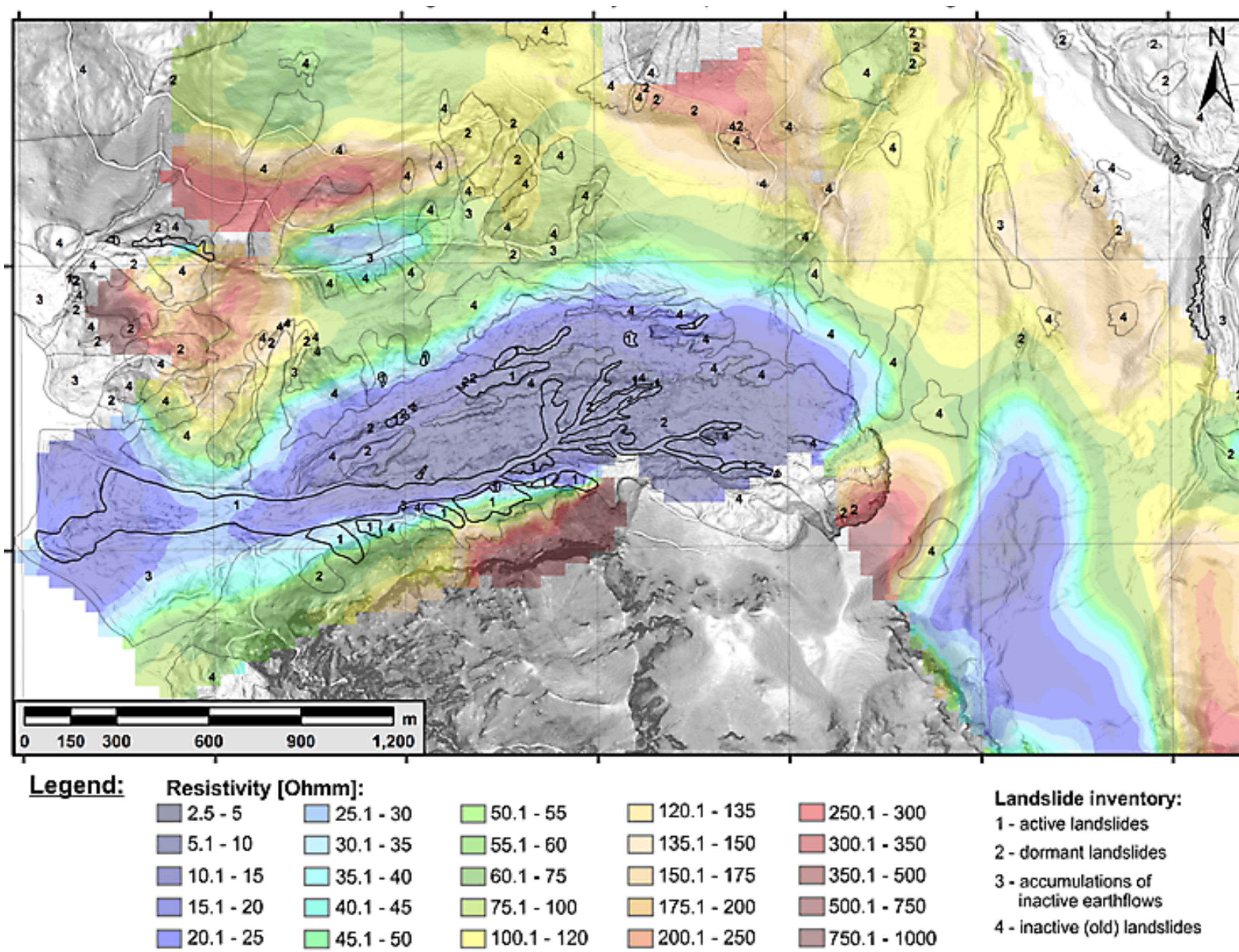
3D view



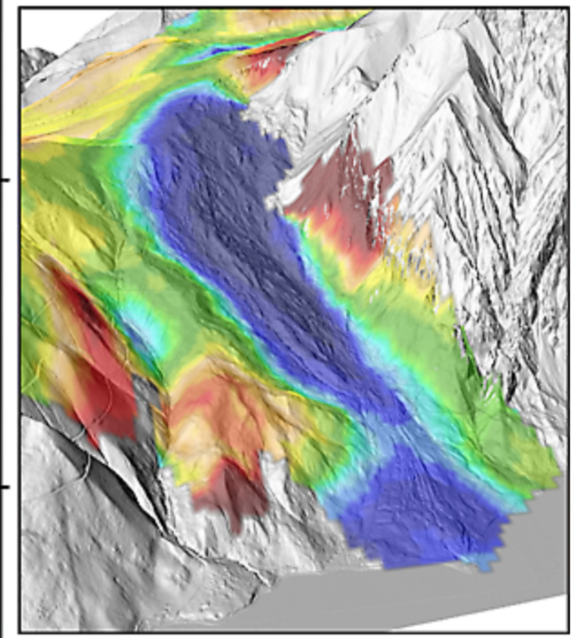
Data & Processing

- Data inverted in 1D

resistivity 20m below surface



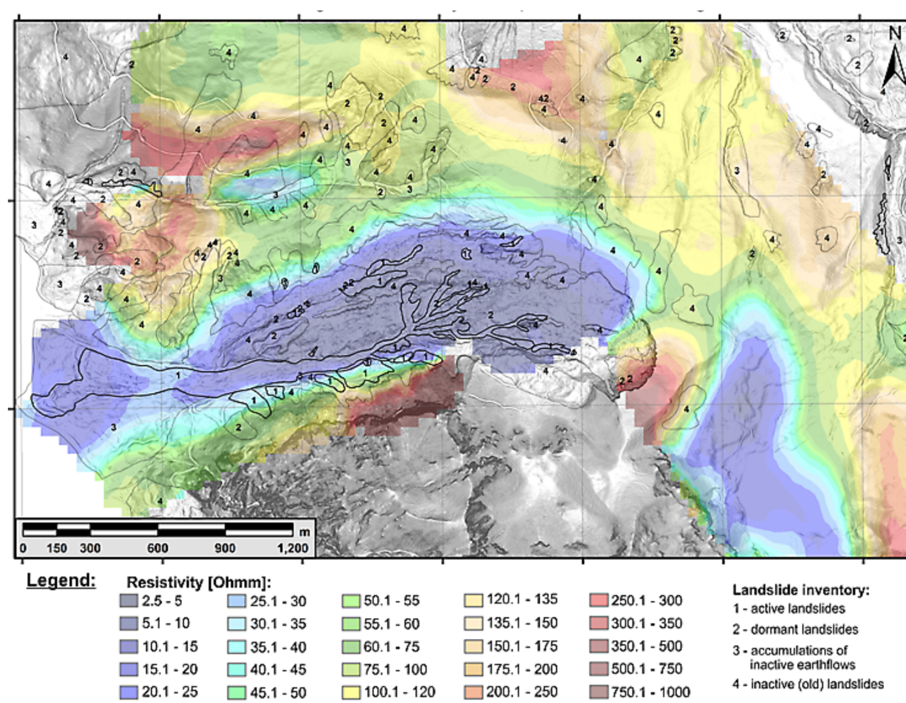
3D view



Interpretation

- 2 – 30 Ωm contour delineates the Buntmergelserie
  - landslide inventory map shows recent landslides are associated with Buntmergelserie
  - Low resistivities show this is most incompetent unit
- Buntmergelserie: highly tectonised
  - Anti-synclinal fold
  - Strongly west-east dipping axis

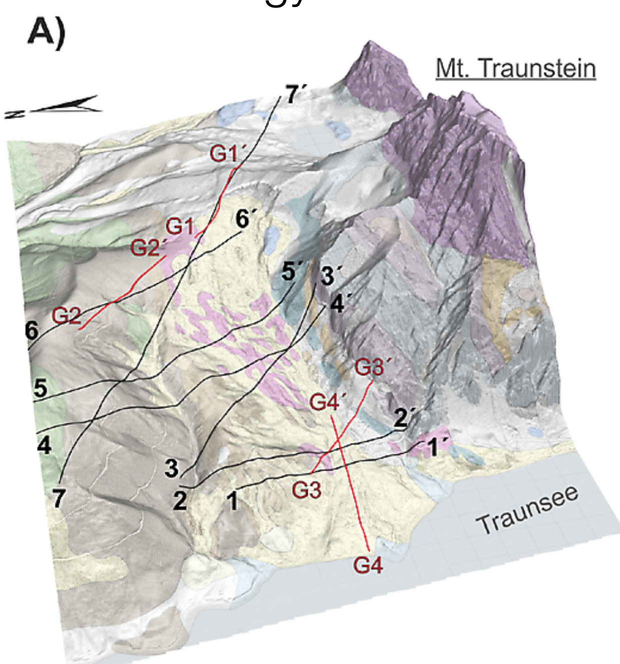
resistivity 20m below surface



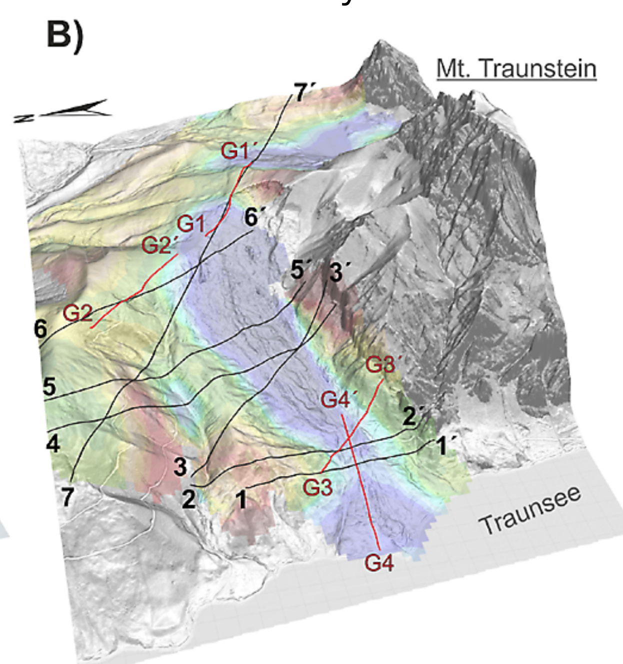
Synthesis

- Airborne EM provided better understanding of the spatial and depth structure of geologic units
- Available model for landslides was significantly improved
  - helped to design proper location of sensors for early warning network for the Gschliefgraben area

Geology

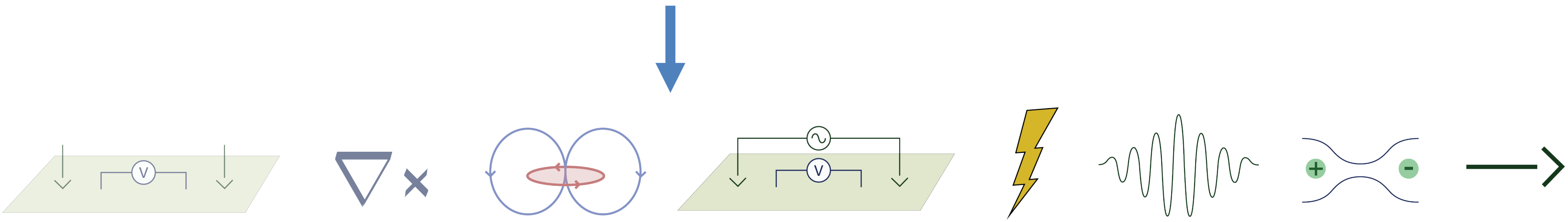


Resistivity



End of Inductive Sources

Next up



DC Resistivity
EM Fundamentals
Inductive Sources
Grounded Sources
Natural Sources
GPR
Induced Polarization
The Future

Lunch: Play with apps

Unexploded Ordnance
(UXO)

Unexploded Ordnance (UXO)

Definition: a munition that was armed, fired and remains unexploded

Sources:
- Regions of military conflict
- Munitions/bombing ranges
- Avalanche control

Countries Significantly Impacted by UXOs

http://www.nohowinc.com/

http://www.dma.state.mn.us/

Various Types of UXO

- Landmines
- Bombs
- Bombies (from cluster bombs)
- Rocket-propelled grenades (RPG)
- Hand-held grenades
- Mortars

How do we find UXO?

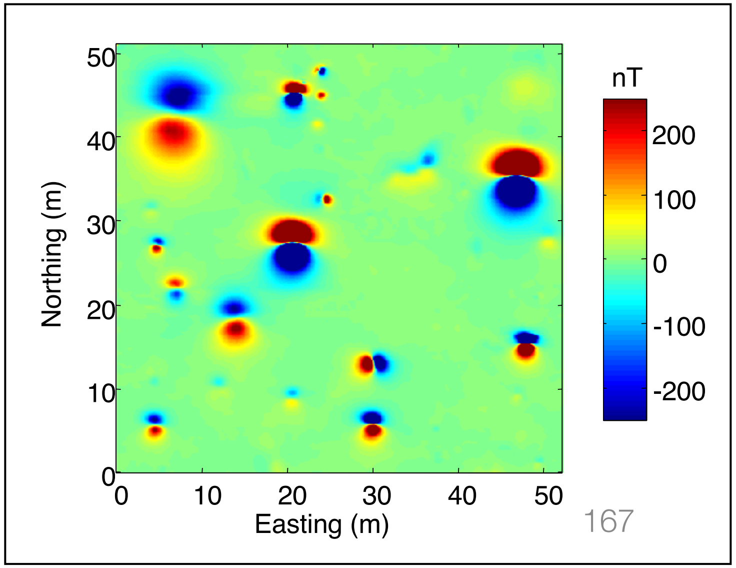
Magnetic Surveys: Locate Anomalies

- Analogue data
- Flag anomaly locations

Ferrex

- Digital data
- Look for magnetic dipoles

TM4



Magnetic Survey: Dig Anomalies

Digital UXO Location and Classification

Problem

- Most anomalies are not UXO
- Digging every anomaly is expensive

Goal

- Classify anomalies
- Dig only UXOs

Strategy

- Need more information than provided by magnetics
- UXO: composed of steel
  - conductive and magnetic

→ Use electromagnetics

Fundamental Physics: EM Survey

- Controlled source generates primary magnetic field
- Primary field induces eddy currents within UXO
- Eddy currents decay over time
- Eddy current produce a secondary field which decays over time

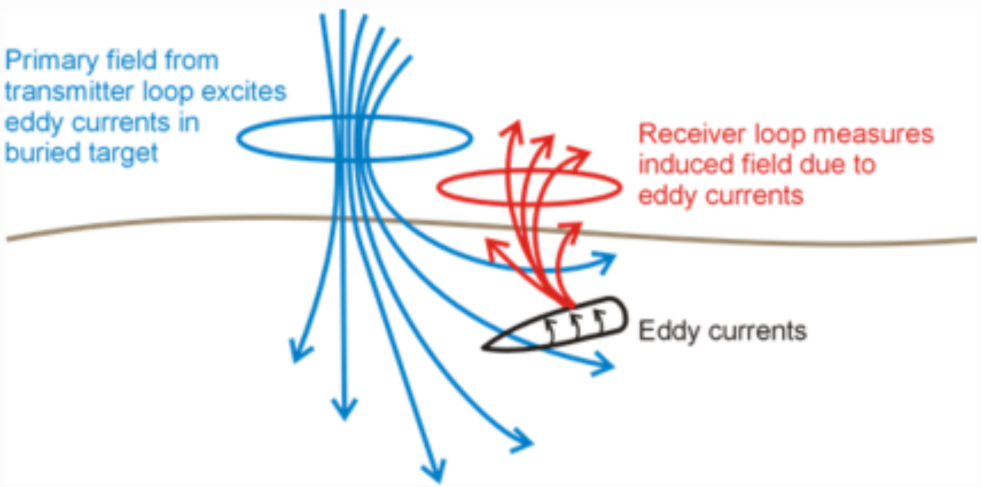
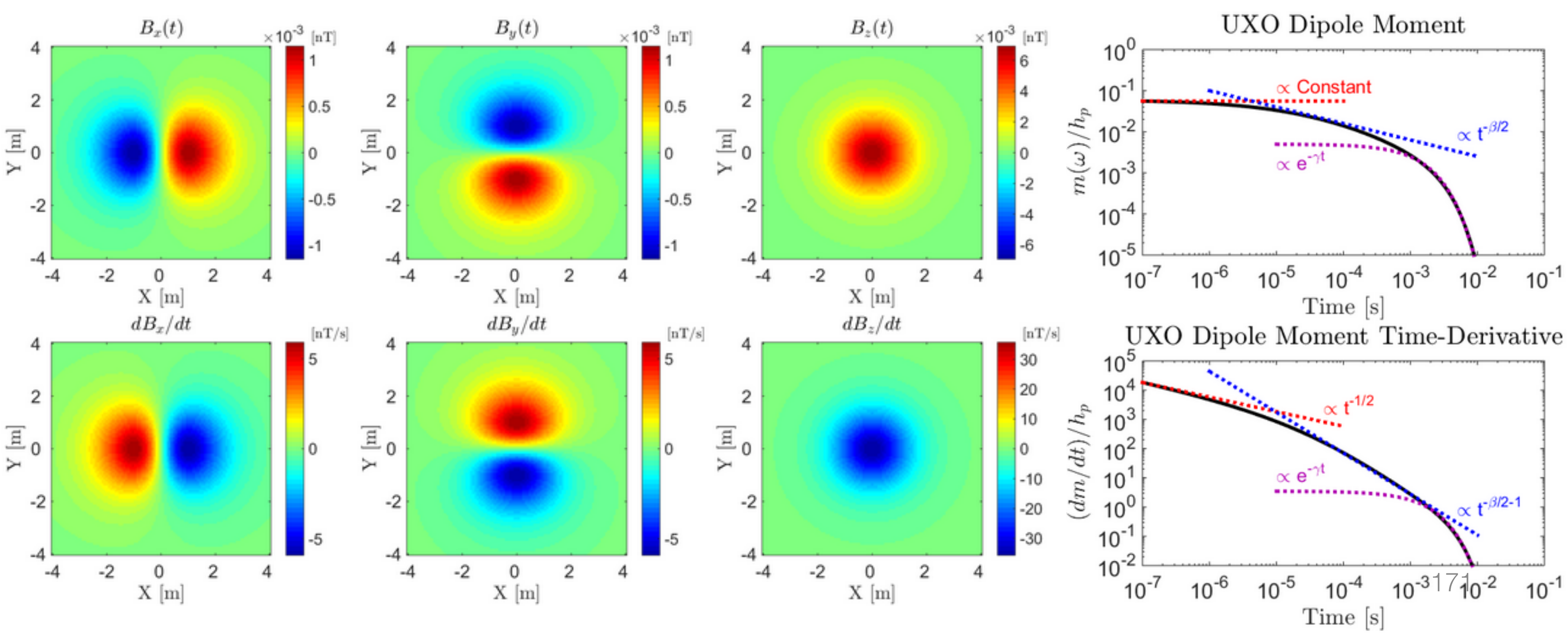


Fig. 260 Electromagnetic induction (EMI) survey for UXO location.

Fundamental Physics: EM Survey

- UXO responses modeled as magnetic dipoles
- Dipoles decay with time
- Rate of decay is indicative of the type of object
- UXOs have characteristic early, mid and late-time decay behaviours

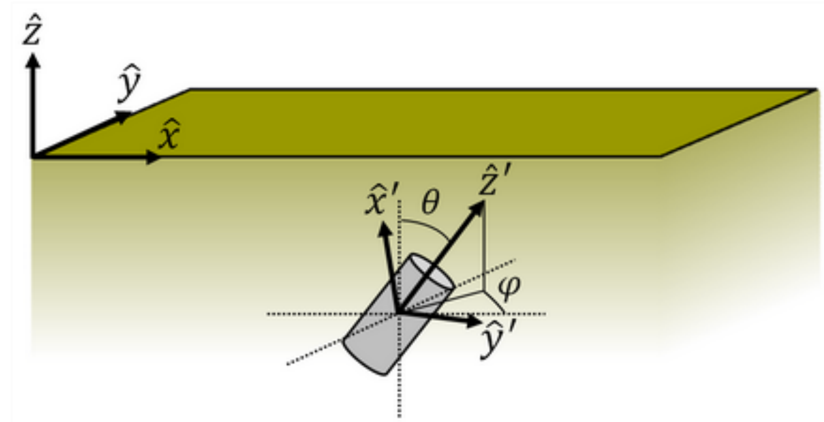


Dipole Model and Polarization Tensor

- UXO response modeled as dipole:

$$\mathbf{b_s}(t) = \frac{\mu_0}{4\pi}\left[\frac{3\mathbf{r}\big[\mathbf{r}\cdot\mathbf{m}(t)\big]}{r^5} - \frac{\mathbf{m}(t)}{r^3}\right]$$

Field and UXO coordinate systems



- m(t) is dipole moment (decays with time)

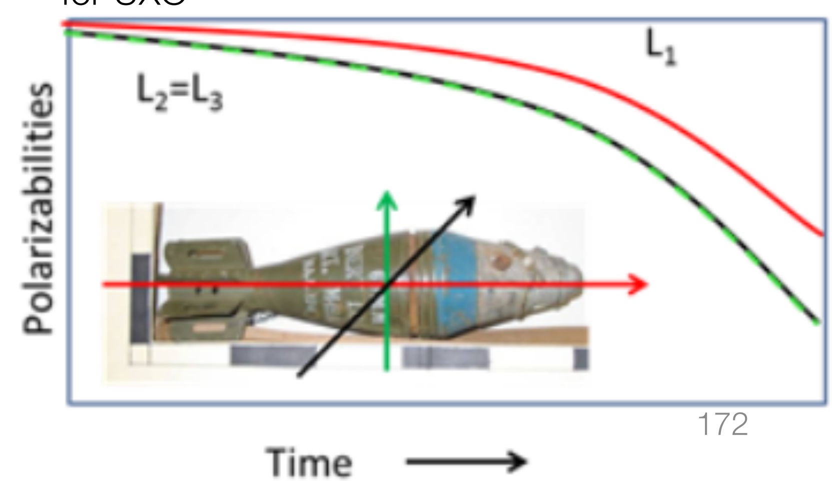
- m(t) depends on:
  1. Orientation of the inducing field
  2. The polarization tensor

$$\mathbf{m}(t) = \mathbf{A^T L A h_p}$$

- The polarization tensor L:

$$\mathbf{L}(t) = \begin{bmatrix} L_1(t) & 0 & 0 \\ 0 & L_2(t) & 0 \\ 0 & 0 & L_3(t) \end{bmatrix}$$

Primary (L1) and secondary (L2,L3) polarizations for UXO



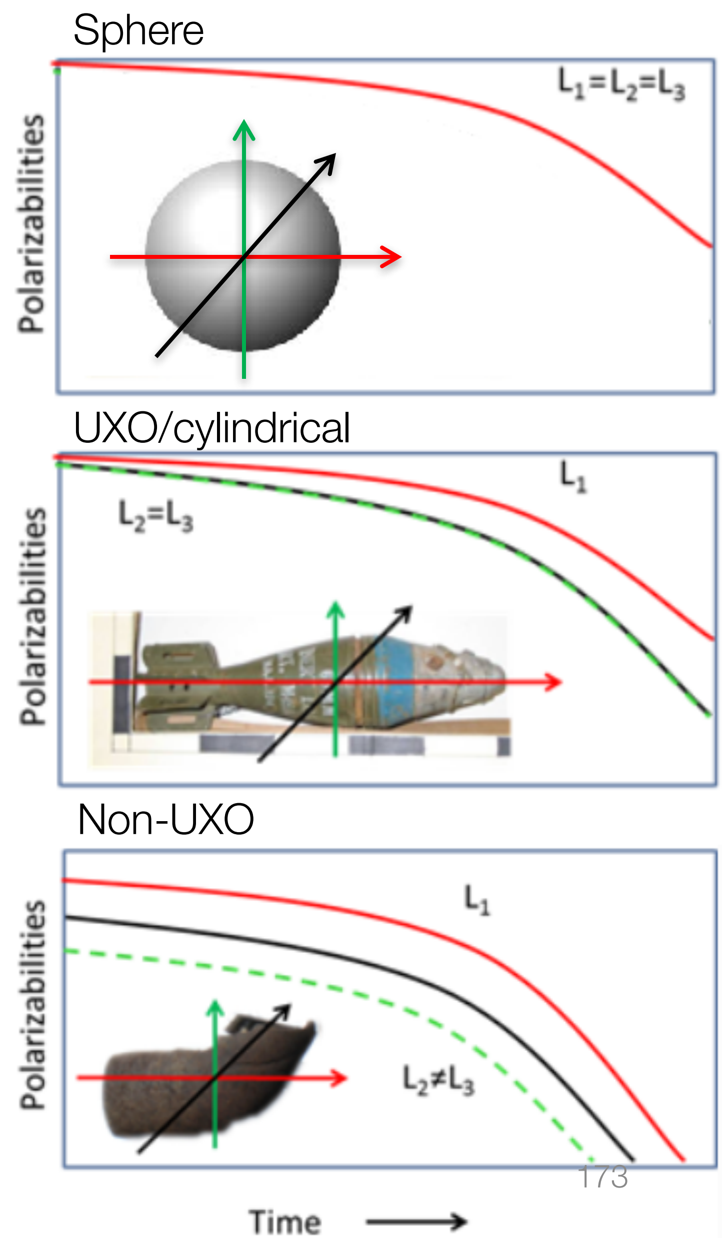
Objects and Polarization Tensors

- Polarization tensor characterizes decay and provides information about dimensionality

- Sphere:
  - Polarization strength independent of primary field direction
  - $L1 = L2 = L3$

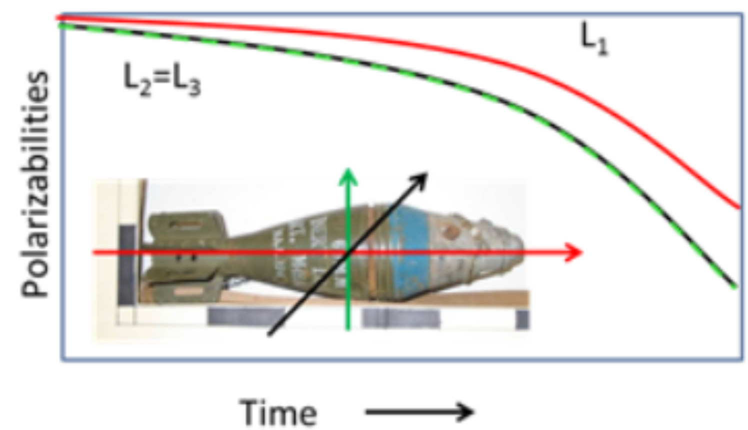
- UXO:
  - Cylindrical in shape
  - Stronger polarization along primary axis
  - $L1 > L2 = L3$

- Non-UXO:
  - Arbitrary shape
  - Polarization different along different orientations
  - $L1 \neq L2 \neq L3$



UXO Classification in Practice

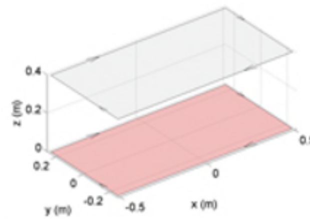
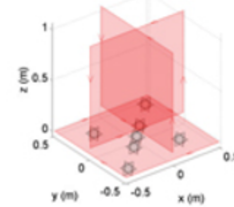
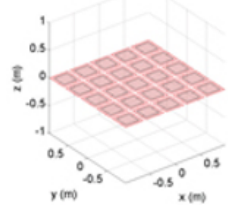
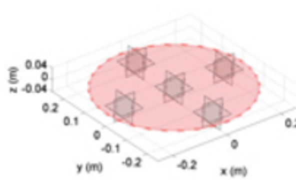
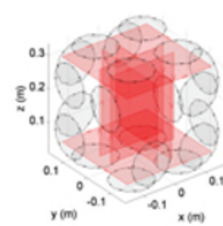
- Survey area and pick targets
- Collect high-resolution data over a target
- Recover the elements of the polarization tensor
- Use the polarization tensor to infer information about the object’s shape
- Match the recovered polarization tensor to those of object stored in a library to classify



To carry out inversion for polarization tensor need data:

- multiple transmitters (orientations)
- multiple components of data

Common Systems

	Sensor	Geometry	Time channels
EM-61	EM-61 		$t_{min} = 0.2\ ms$ $t_{max} = 1.5\ ms$ $N = 4$
MetalMapper	MetalMapper 		$t_{min} = 0.1\ ms$ $t_{max} = 10\ ms$ $N = 42$
TEMTADS	TEMTADS 		$t_{min} = 0.1\ ms$ $t_{max} = 20\ ms$ $N = 115$
MPV	MPV 		$t_{min} = 0.1\ ms$ $t_{max} = 20\ ms$ $N = 32$
BUD	BUD 		$t_{min} = 0.1\ \mathrm{ms}$ $t_{max} = 1.5\ ms$ $N = 45$

Survey Design

Line and Station Spacing:

- Depends on dimensions and depth of targets and system being used.
- Insufficient sampling makes locating and classifying targets more challenging.

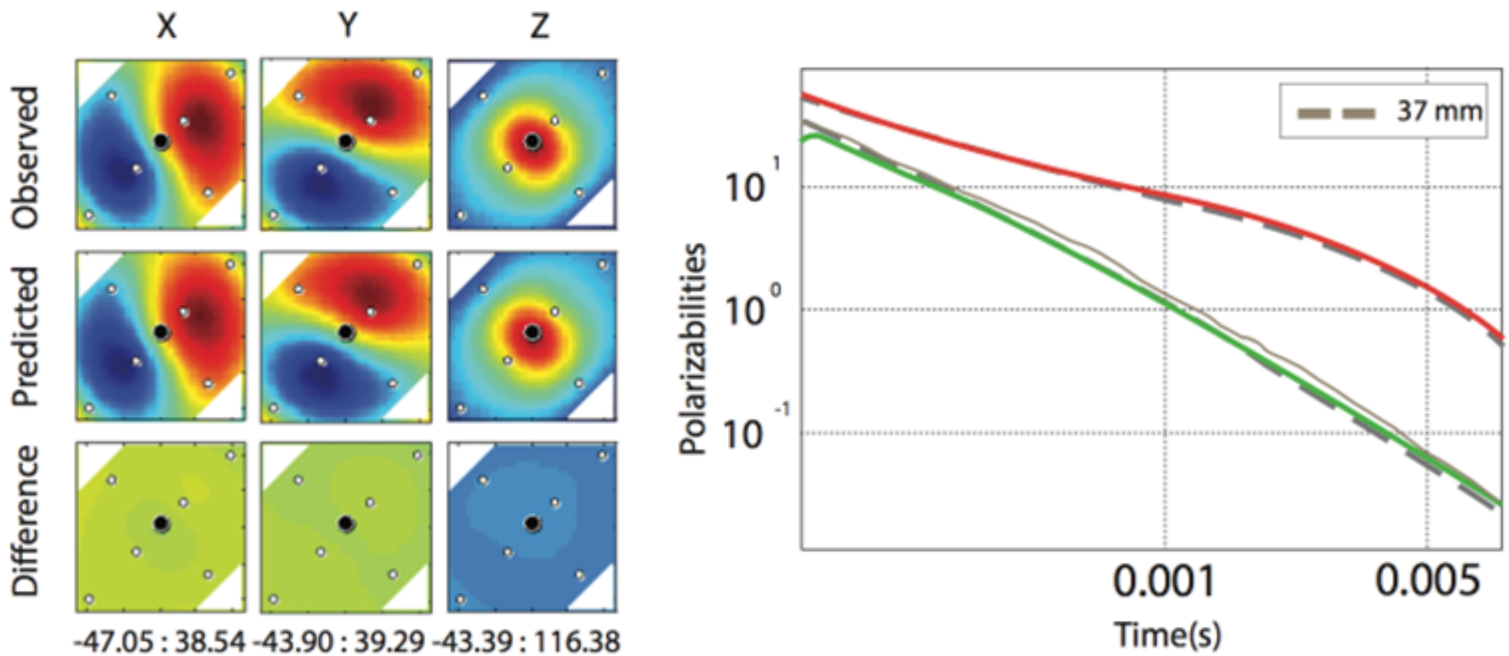
Excitation Orientation

- To recover polarization tensor, target must be polarized from as many angles as possible.
- May require multiple passes with single transmitter or use of multi-transmitter system.

Time Channels

- Sufficient time-channels required to characterize decay behaviour.

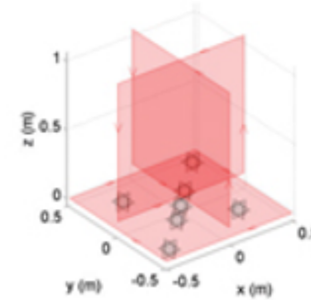
Example: Metal Mapper Data

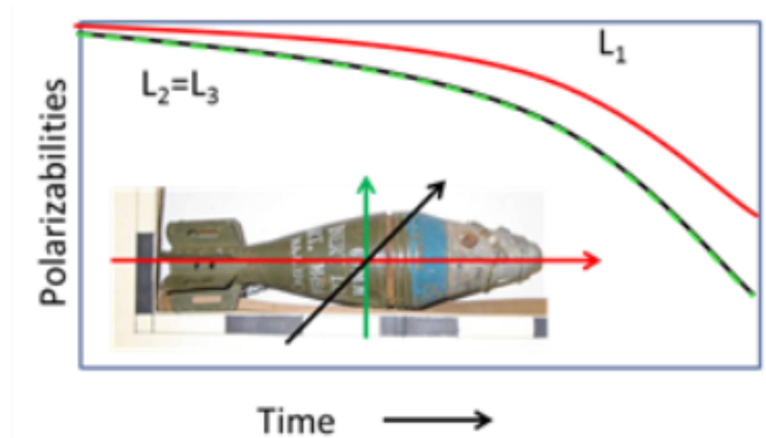


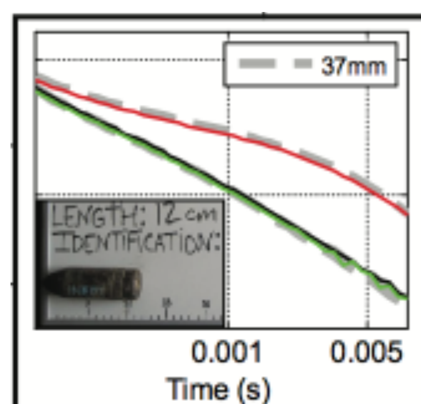
- Polarizations indicate a cylindrical object
- Predicted data using recovered polarization tensor fits the observed data
- Recovered polarizations match those of a 37 mm projectile

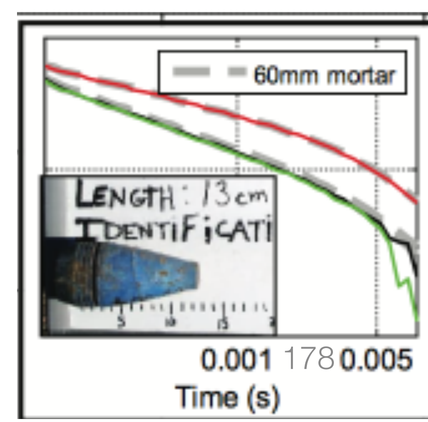
Summary

- UXO are compact conductive permeable objects
- EM is ideal survey
- Requires multiple transmitters and receivers
- Processing yields polarization curves
- Discrimination









Field Example: Pole Mountain

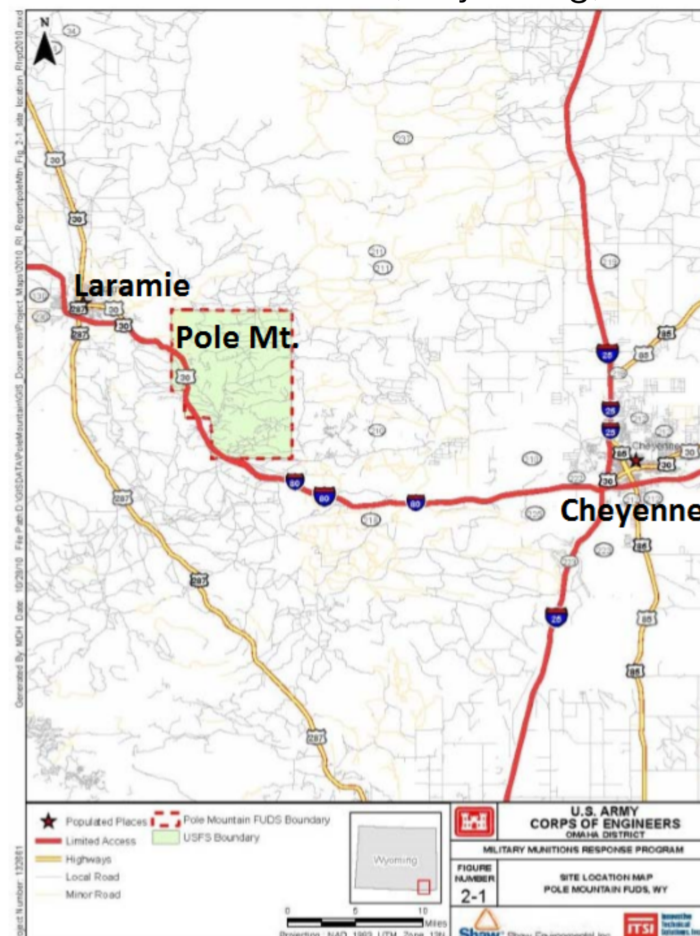
History

- Periods of military use 1897-1961
- Many types of munitions (explosive projectiles, mortars, small arms)
- Land reclamation currently not possible

Goals:

- Test classification algorithm on different objects
- Determine dig/no dig list for targets

Location of Pole Mt., Wyoming, US



Field Example: Pole Mountain

EM61-MK2:

- Efficient over rugged terrain
- Single Tx and Rx loops
- Located 2,368 anomalies

Metal Mapper:

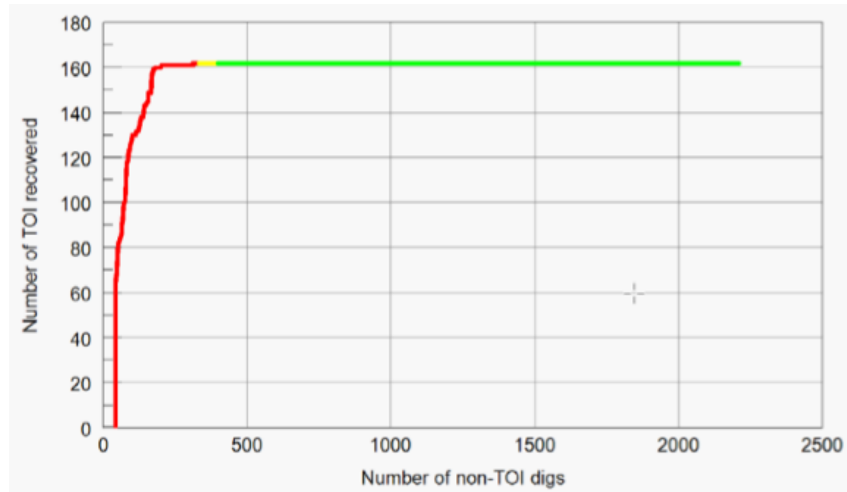
- Multiple Tx and Rx loops
- Cued interrogation data over anomalies
- Data used for classification and prioritize dig list

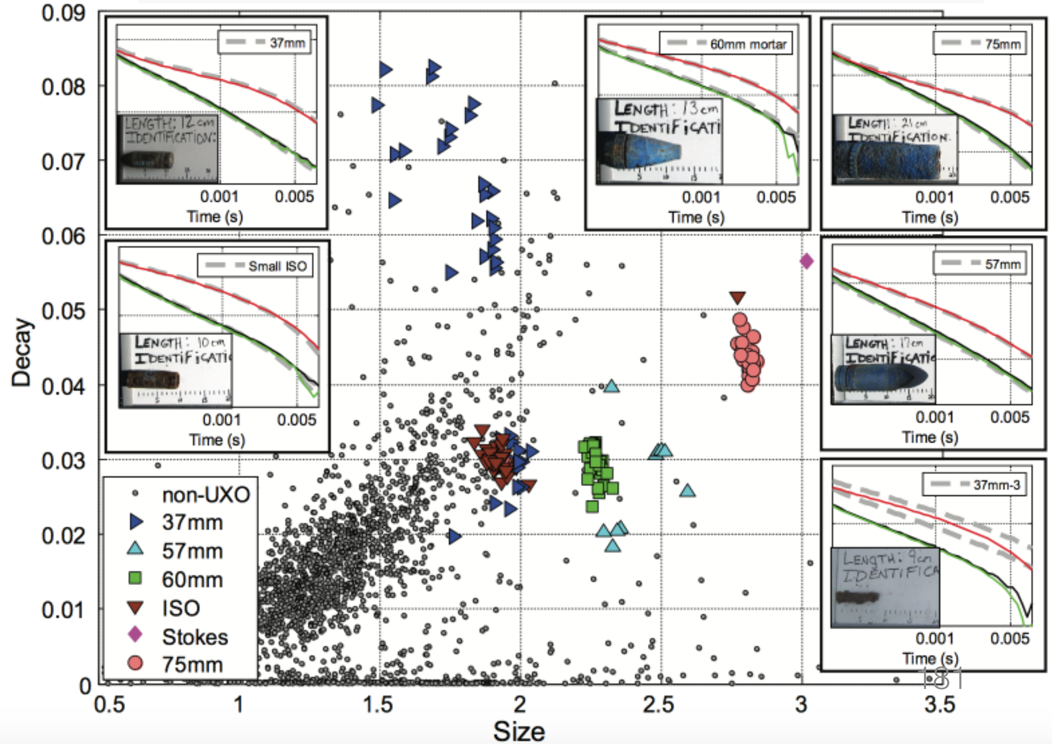
EM61-MK2 (locate anomalies)

Metal Mapper (cued interrogation)

Field example: Pole Mountain

- All 2,368 TEM anomalies were dug to verify
- 1,829 correctly identified as clutter or assigned to no dig through classification
- Only 453 non-munition items dug before all 160 munition items dug.
- 99% of munition items located within first ~300 digs
- Correctly identified all types of munititons.





End of Inductive Sources